Latest Advances in the Microwave Observatory of Subcanopy and Subsurface (MOSS) Project

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Investigation Team

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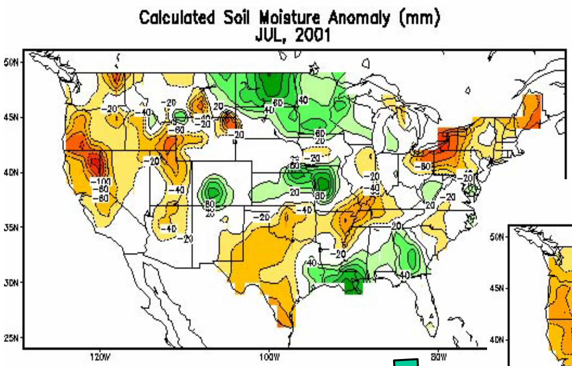
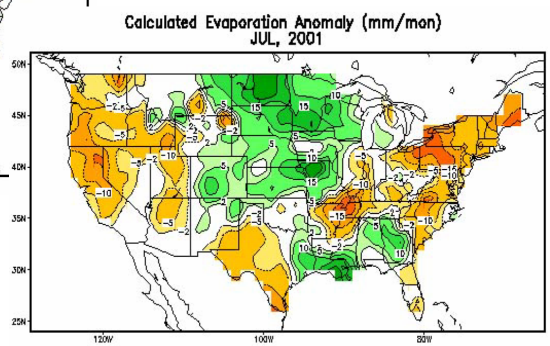
  - Mark Thompson, Michael Parker (Northrop Grumman)

MOSS At-A-Glance

- This instrument incubator addresses a key research issue for the Global Water and Energy Cycle: **measuring soil moisture under "substantial vegetation canopies and at useful soil depths"**
- The proposed system is a UHF/VHF SAR that delivers data for estimation of soil moisture
  - down to 1-5m depth
  - through 200 tons/ha or more of vegetation
  - at 1-Km resolution
  - globally once every 7-10 days.
- Key hardware technology challenge addressed is a low-cost, low-mass, low-risk, 30-m long dual-frequency antenna to accommodate a wide swath for the rapid observation cycle.
- MOSS will deliver:
  - Antenna design and prototype dual-frequency antenna feed system
    - Advance TRL from 3 to 5
  - Prototype science data set
  - Prototype soil moisture estimation algorithms
  - Science impact for global water and energy cycle and its interplay with the carbon cycle

Science Significance

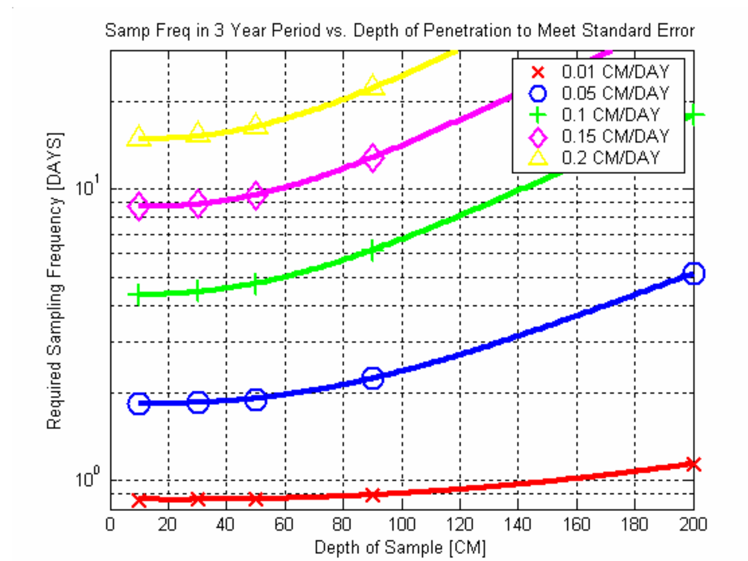




- Soil moisture profile down to the root zone controls global hydrologic partitioning into evaporation, transpiration, runoff, and drainage.
- Quantifying evaporation is required to address ESE priority science questions about the <u>water cycle</u> as well as the <u>carbon cycle</u>:

> Is the water cycle accelerating due to global change?

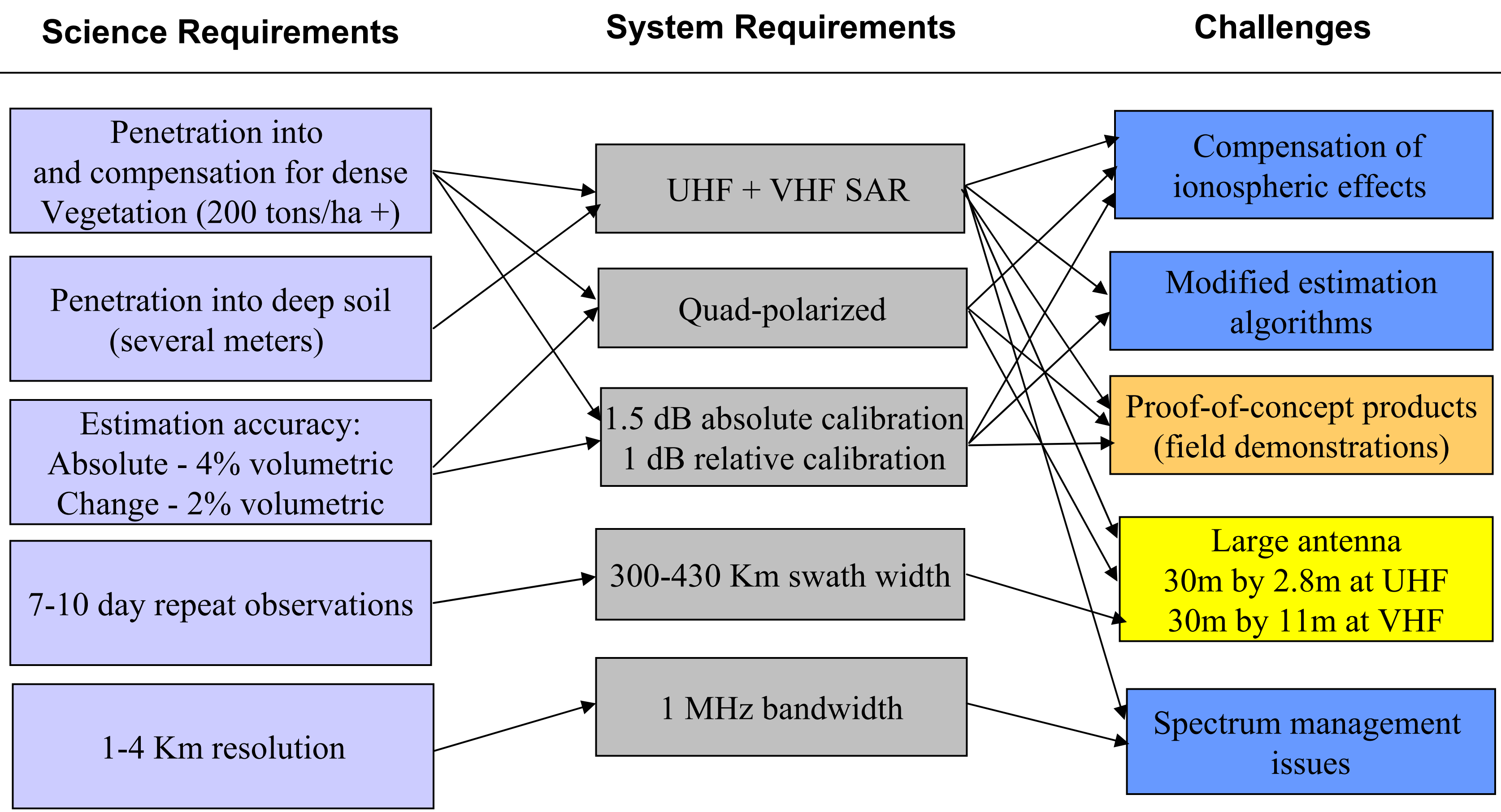
> What is the magnitude of carbon sequestration in global forests (a major portion of the 'missing sink')?



- Observed soil moisture (%) shows that depletion of moisture by evaporation extends deep into the soil.
- Deep moisture sampled at longer intervals (7-10 days) has the same impact on water balance estimation as surface/shallow soil moisture sampled rapidly (2-3 days).

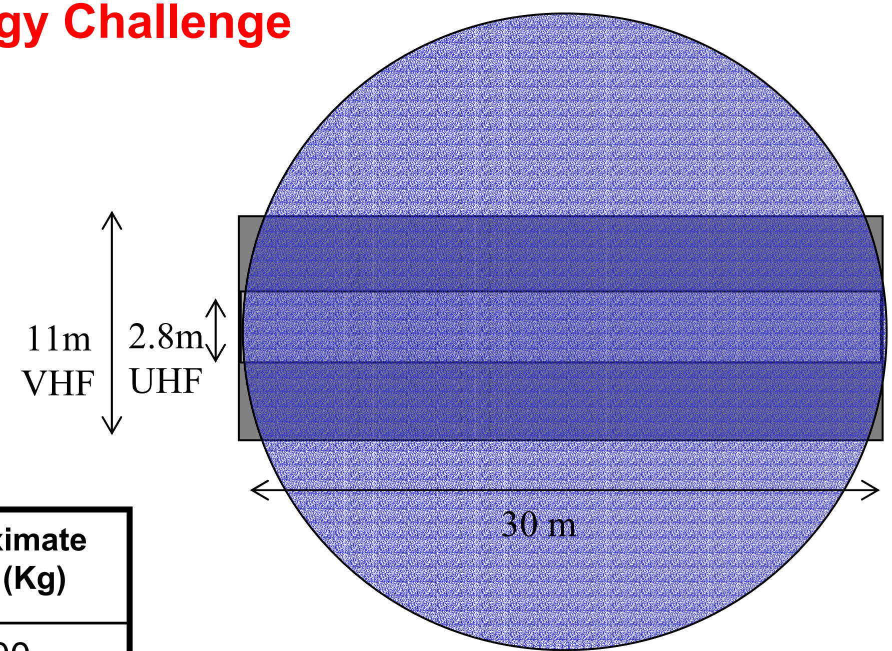
Entekhabi

Requirements Flow-Down

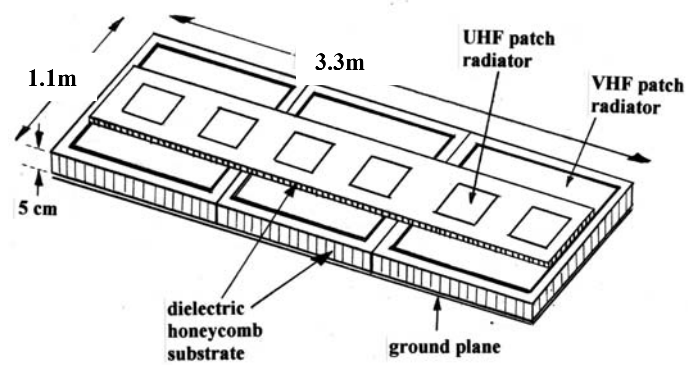


Key Technology Challenge

- Key hardware technology item for a future spaceborne mission is the 30-m long, dual-width antenna
- Mass savings of our approach over current technology is ten-fold
- Significantly lower risk than other proposed technologies such as inflatable apertures



Antenna Implementation	Approximate mass (Kg)
Two planar arrays (30mx3m and 30mx11m), state-of-technology (LightSAR), 10kg/m^2	4200
Dual-frequency shared aperture planar array, state-of-technology (lightSAR) shared segment (30mx3m): 15kg/m2, remaining segment (30mx8m): 10kg/m2	3750
Passive mesh reflector with dual-frequency feed (this IIP concept), 15kg/m2 for feed, ~300 Kg for 30m mesh reflector	~ 400



Dual-stacked patch feed for synthesizing highly shaped apertures on reflector

Project Overview

Project Goals

- **Antenna design and feed prototype**
    - Generate SAR system-level design for spaceborne mission
    - Carry out detailed design of dual-low-frequency radar reflector+feed antenna system
    - Build and test a complete scaled model of the shared planar array single feed structure
    - Build and test the full-size feed structure
    - Generate the reflector antenna and S/C mechanical design
- **Generate sample science data and soil moisture products**
    - Construct a validation science data set through ground experiments and tower radar
    - Wide range of vegetation and soil moisture conditions: arid/semiarid, temperate forest, temperate grassland, boreal forest
    - New-generation low-frequency radar soil moisture estimation algorithms
- **Devise methods to mitigate ionospheric effects**
- **Assess impact on global change studies**
    - Test the sensitivity of hydrological cycling models to soil moisture products from this instrument set
    - Assess impact of products from this instrument set on ecological and global change studies
- **Perform spectrum analysis for interference to/from other systems**
    - Obtain US NTIA stage 1 approval for operation on a non-interference basis

MOSS SAR System Design

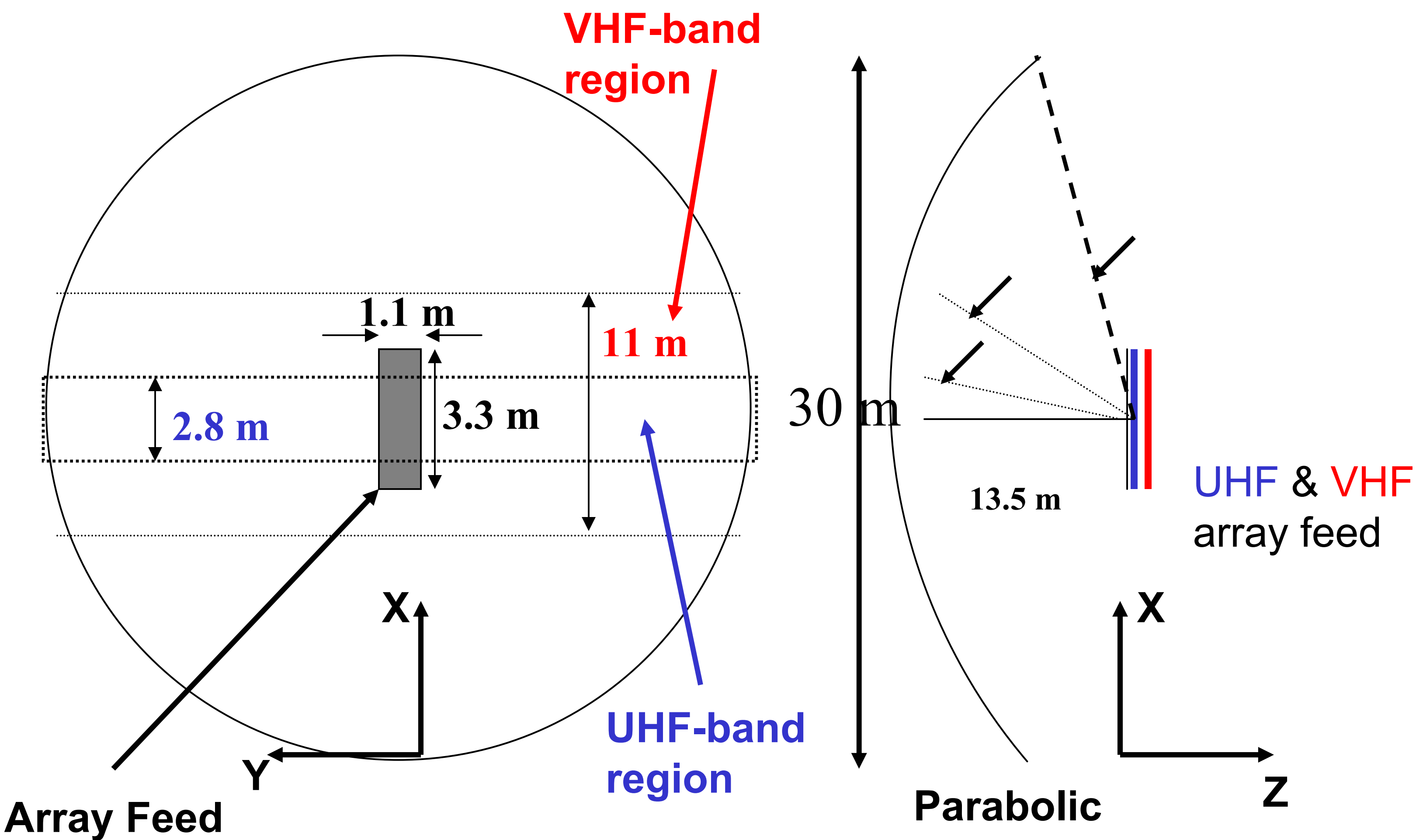
System Design Parameters

Parameter	UHF	VHF
Altitude	1313 km	1313 km
Swath Width	346 km	346 km
AntennaWidth	2.8m	11m
AntennaLength	30m	30m
CenterFrequency	435 MHz	137 MHz
Bandwidth	1 MHz	1 MHz
No.Looks/1km(min.)	54	40
Peak Power(1 channel)	2kW	2 kW
Pulse Length	140usec	140usec
Duty Cycle(2 channel)	13%	13%
Avg. Power(2 channel)	255W	255W
PRF (1 channel)	455Hz	455Hz
ProcessingBandwidth	137Hz	182Hz
Data Rate (dual channel)	1.7Mbps	1.7Mbps
IncidenceAngle Range	16-32	16-32
Azimuth Ambiguities	-18dB	-20dB

- The PRF is maximized to lower the azimuth ambiguities to manageable levels while maintaining an acceptable swath width (346km)
- A long pulse width (140us) is used for both systems enabling a relatively low transmit power (2kW peak)
- The data rate estimate assumes block floating point quantization (~4bits/sample) and does not take into account the land/ocean duty cycle

Antenna Design Concept

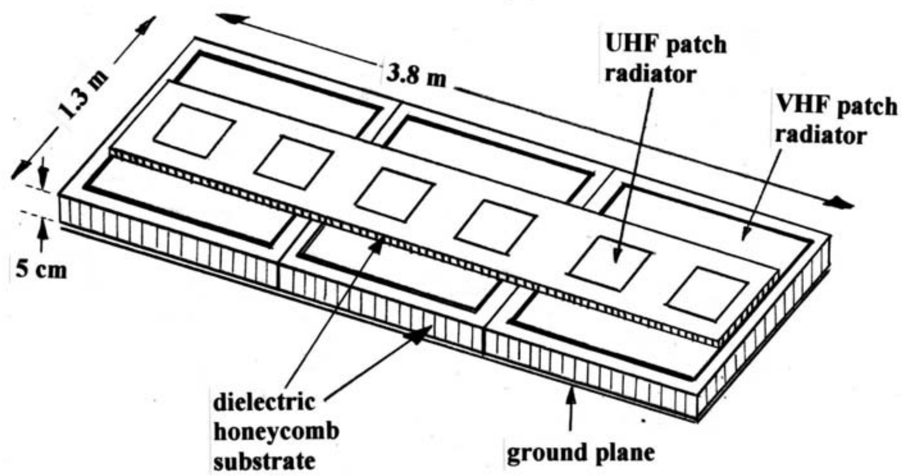
30-m Reflector Antenna and Feed Geometry

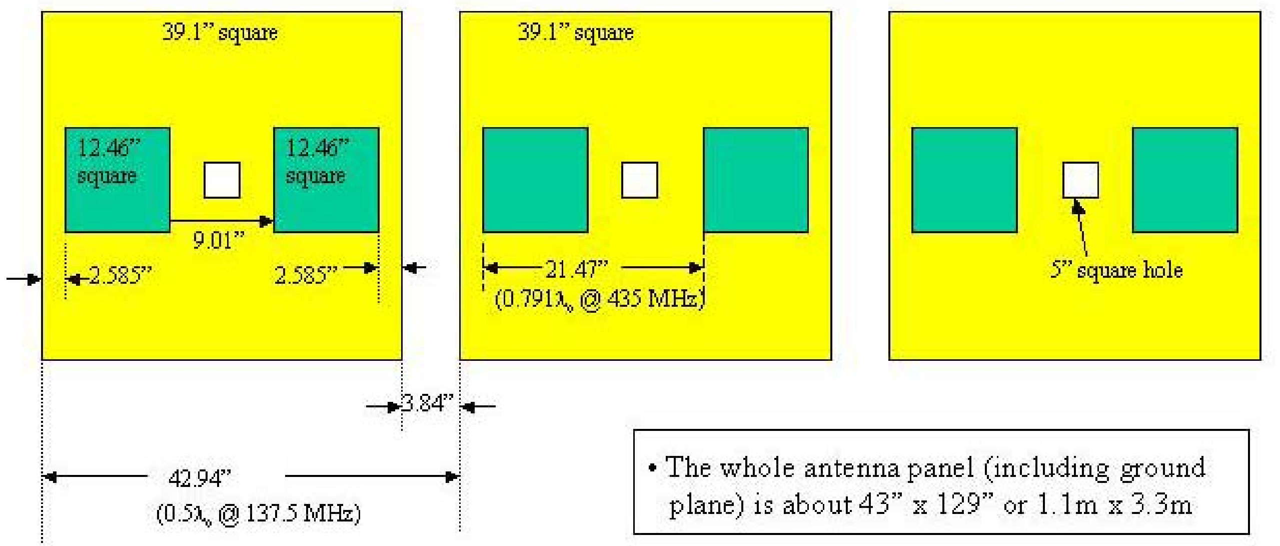


F/D=0.45

Antenna Feed to Achieve Reflector Under-illumination

Dual-band Stacked Patch Configuration





- The whole antenna panel (including ground plane) is about 43" x 129" or 1.1m x 3.3m

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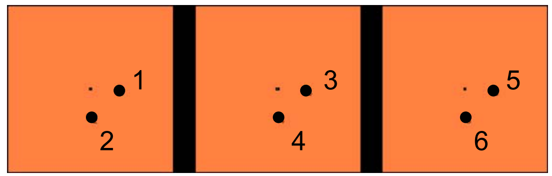
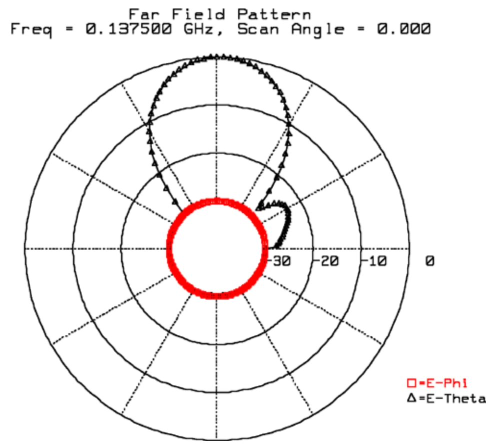
Feed Array Pattern at VHF

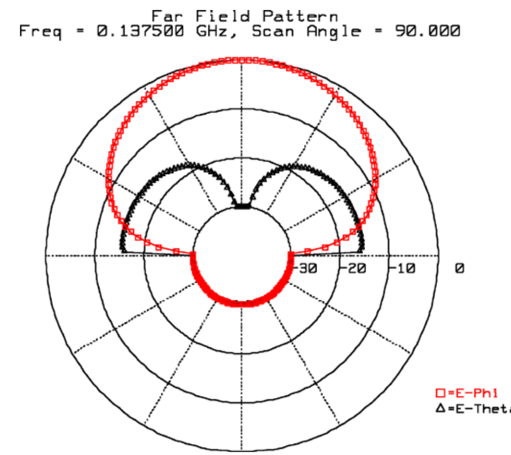
Dual-band Stacked Patch Theoretical Patterns



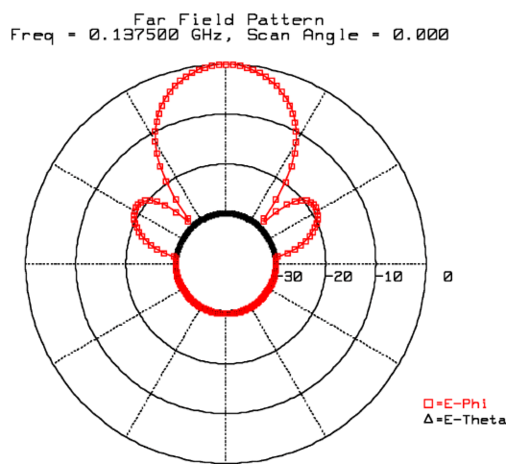
3-element patch array patterns at 137.5 MHz

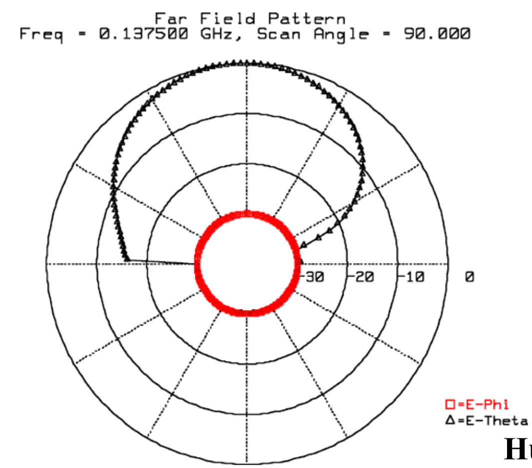
H-port principal-plane patterns for probes 1,3 and 5 (single element)





V-port principal-plane patterns for probes 2,4 and 6 (single element)





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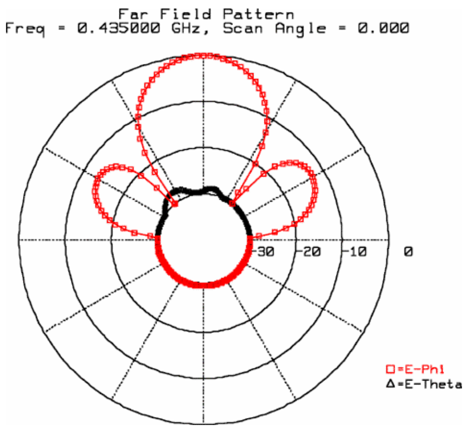
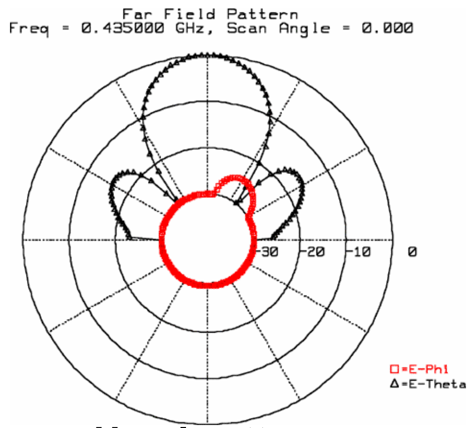
Antenna Feed Design



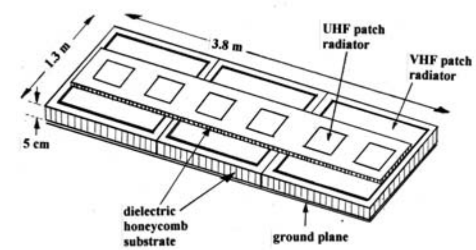
V-pol pattern

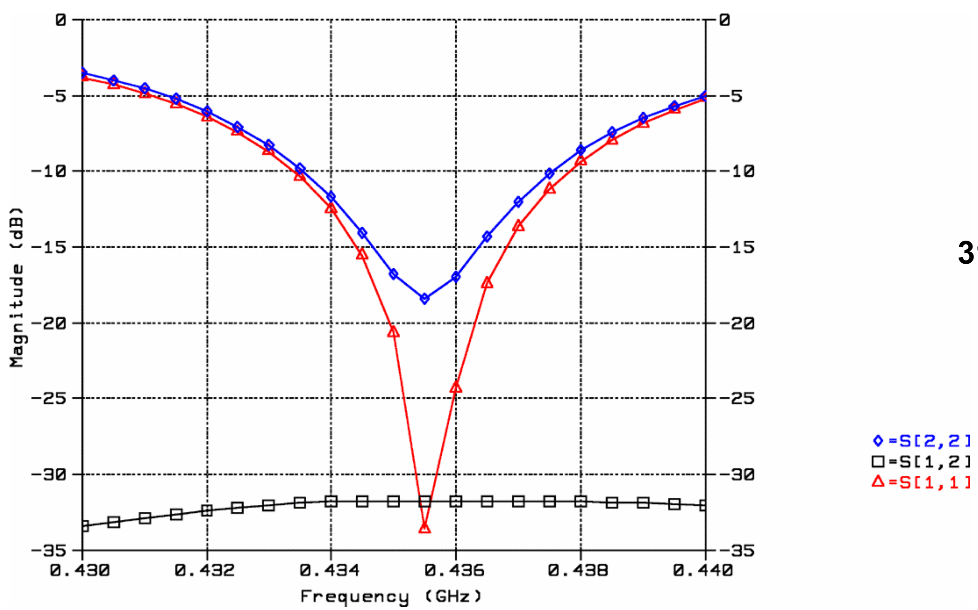


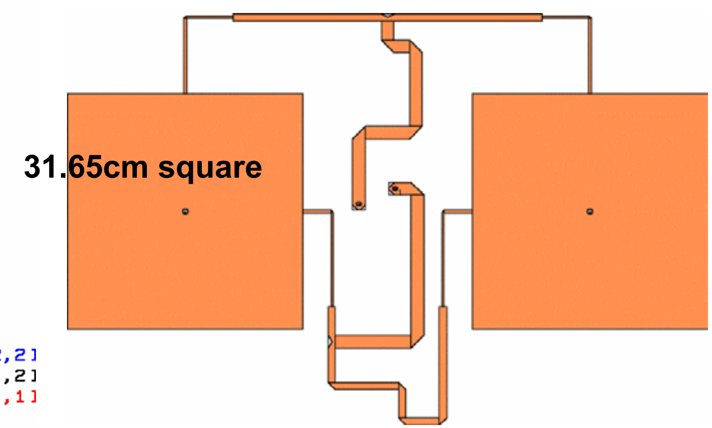
H-pol pattern

Two UHF Patches per VHF Patch Combined by Microstrip Lines

(Designed and calculated results)







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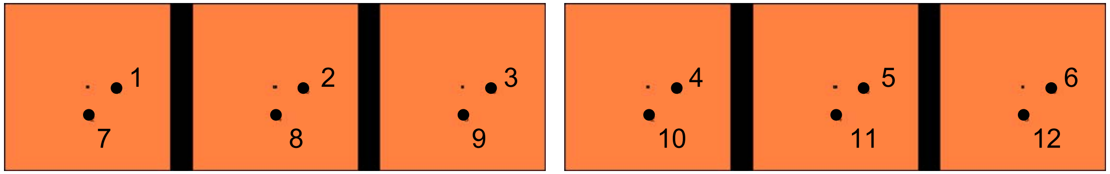
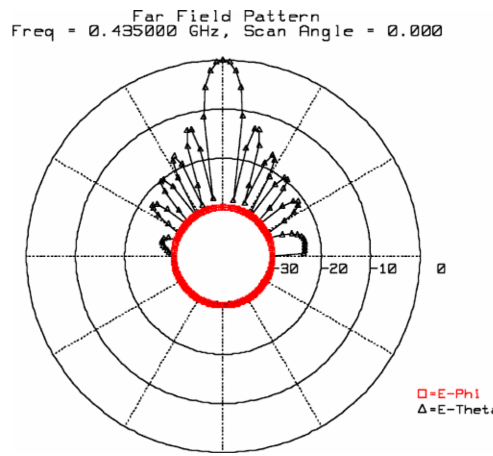
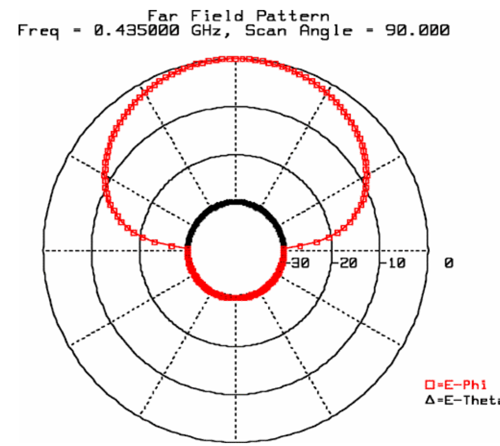
Feed Array Pattern at UHF



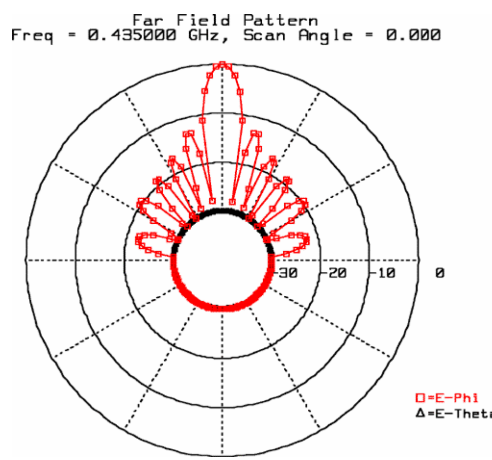
6-element patch array patterns at 435 MHz

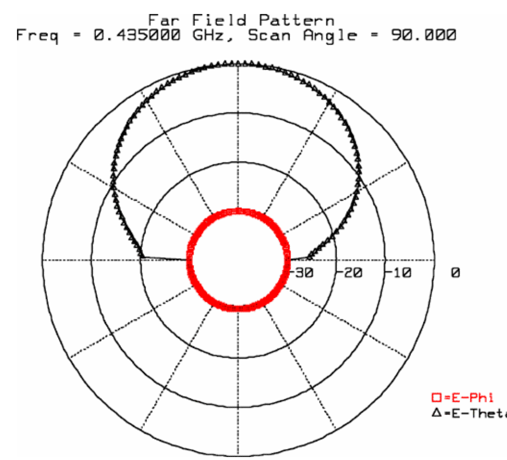
H-port principal patterns for ports 1 through 6





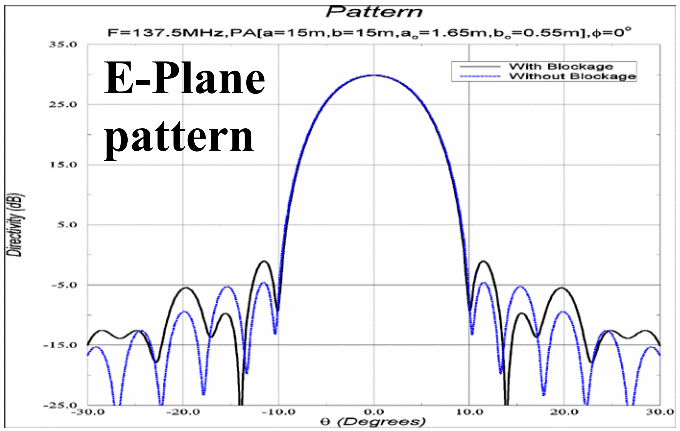
V-port principal patterns for ports 7 through 12

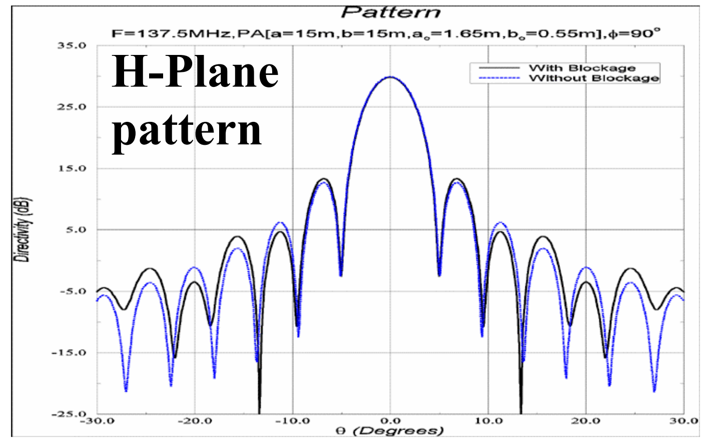


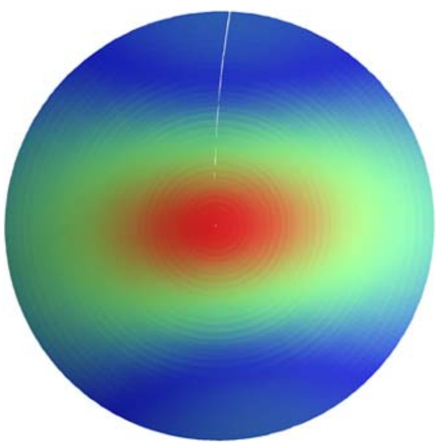


Effective Rectangular Aperture

30 meter Parabolic Antenna Currents
Freq=137.5 MHz





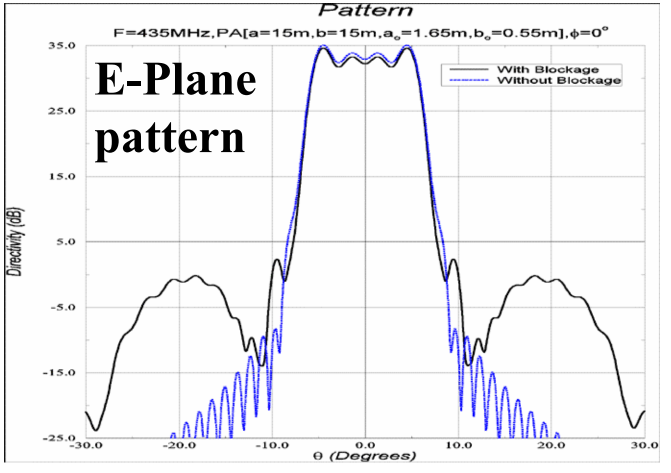


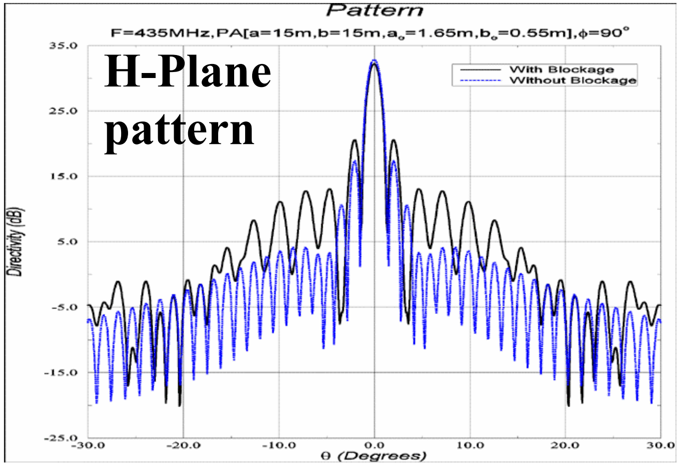
Current on the reflector

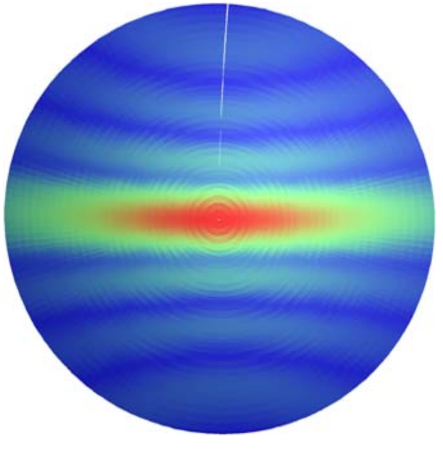
Directivity (No Blockage)	Directivity (With Blockage)	Array blockage loss	HPBW (E-plane)	HPBW (H-plane)
29.87 dB	**29.69 dB**	**0.18 dB**	**8.4°**	**4.2°**

Effective Rectangular Aperture

30 meter Parabolic Antenna Currents
Freq= 435 MHz





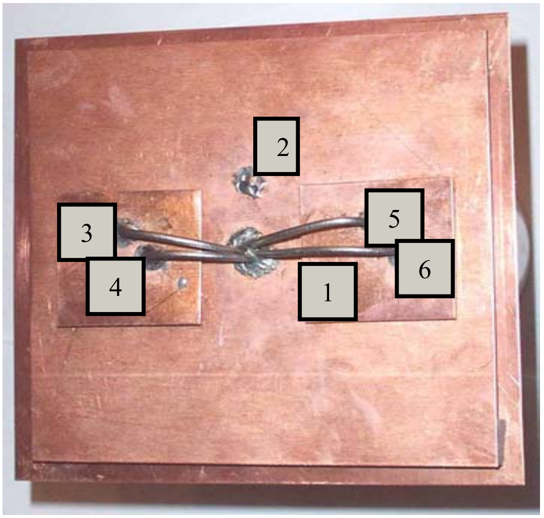


Current on the reflector

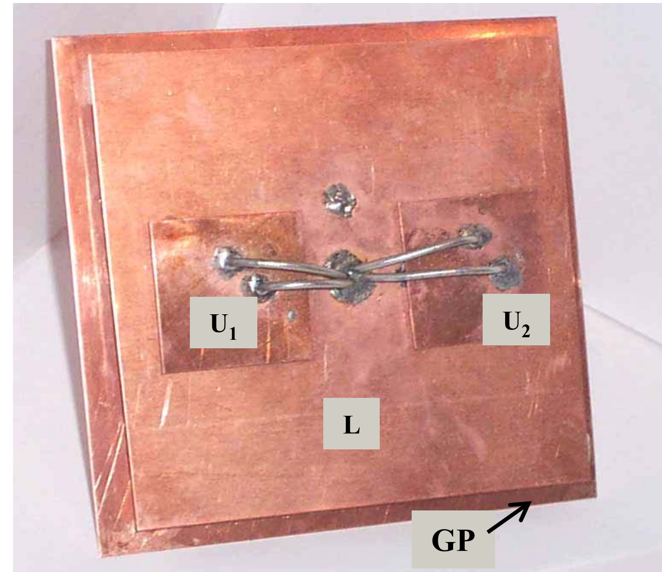
Directivity (No Blockage)	Directivity (With Blockage)	Array blockage loss	HPBW (E-plane)	HPBW (H-plane)
32.84 dB	**32.27 dB**	**0.57 dB**	**11.6°**	**1.2°**

Proof-of-Concept: Antenna Feed at Scaled Frequencies

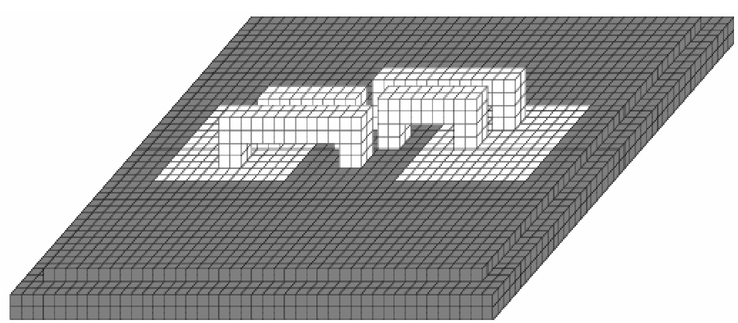
Dual–Frequency Dual-Polarization Stacked Patch Feed Design, L/S bands



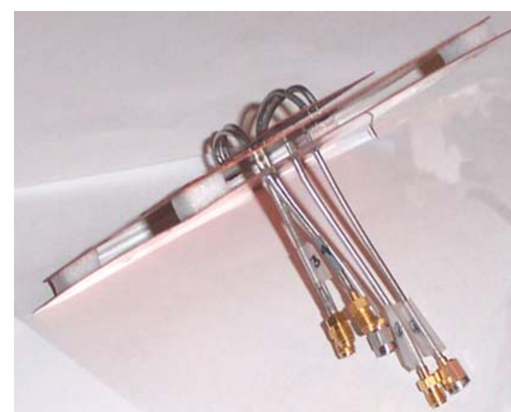
Stacked patch built at Antenna Lab (UCLA)
1 and 2 are the feed points for lower patch
3,4,5 and 6 are the feed points for the upper patch



Top-view of Stacked Patch



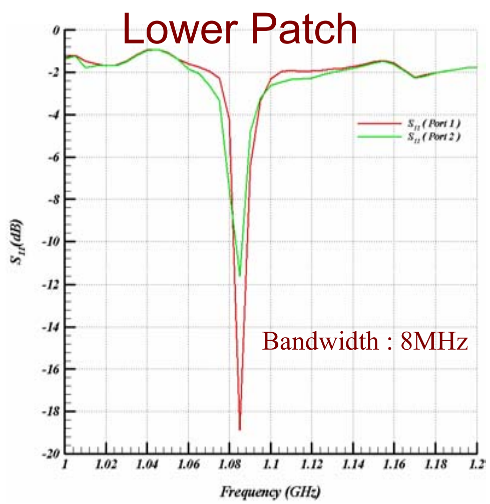
Grid used in FDTD Simulation of Stacked Patch

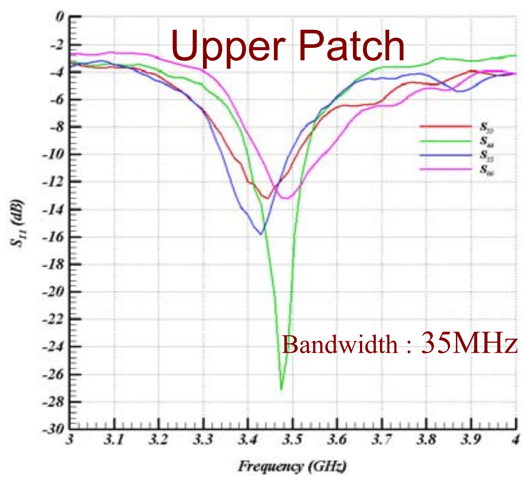


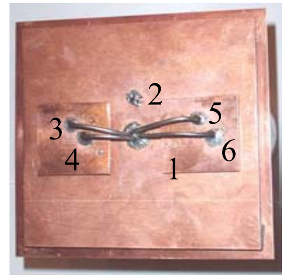
Side-view of Stacked Patch

Antenna Feed at Scaled Frequencies, Single Patch

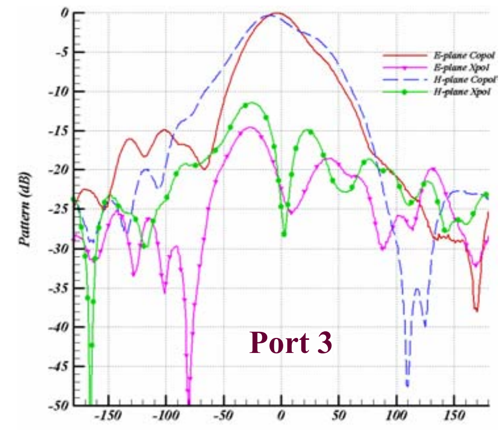
S_{NN} Measurement Results for Stacked Patch Array Element

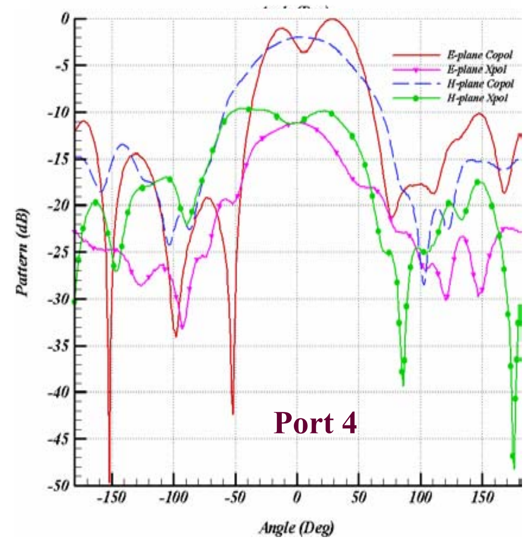






Measured Radiation Pattern for Stacked Patch (Upper Patches)





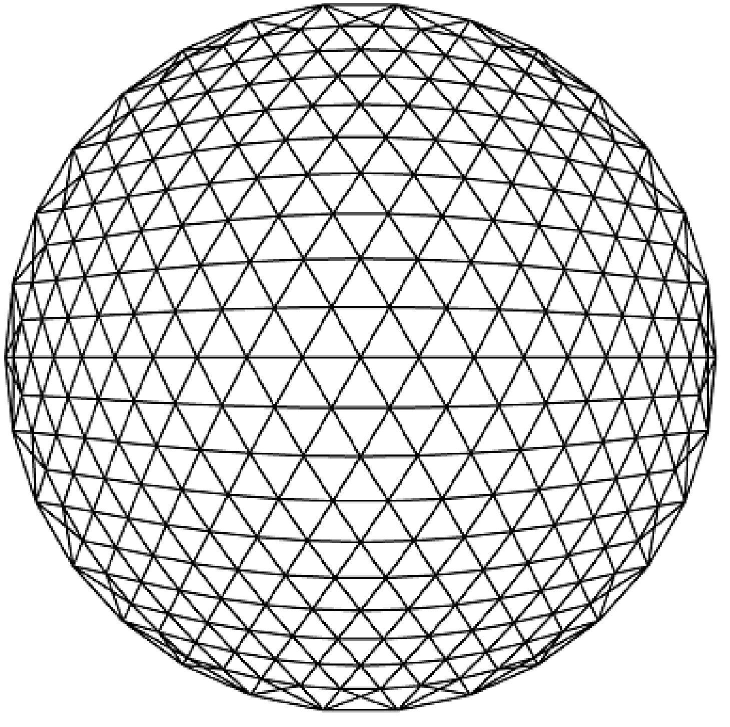
Fully populated array is currently under construction. Will advance to TRL 4 upon successful testing.

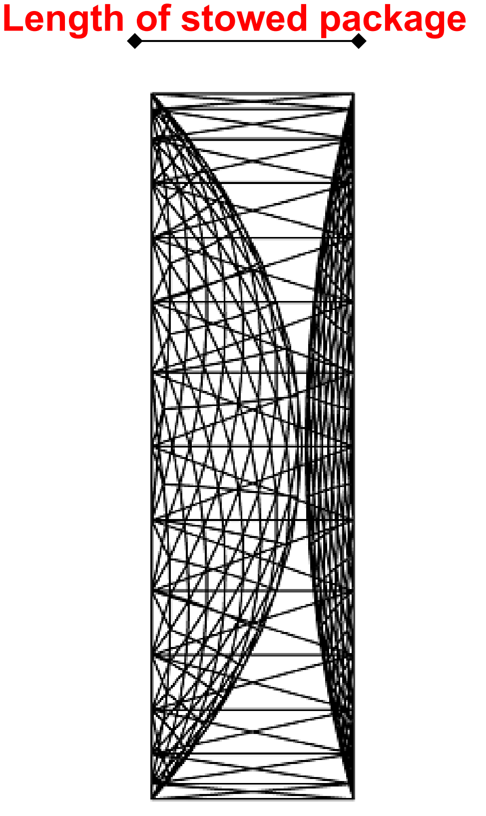
Phase 1 Study Objective

- Determine the spacecraft architecture so that the general design space and important constraints on the MOSS 30 m radar antenna can be assessed.
- Generate a preliminary set of general reflector and feed support structure requirements. These requirements will emphasize the spatial and (kinematic) deployment requirements that confront us based upon realistic deployed S/C configurations and launch vehicle and bus volumes.
- Investigate potential S/C architectures

30-m Reflector Mechanical and S/C Design

- Front net depth is 6.45 m for F/D = 0.3
- Batten Length is 8.67 m
  - AM2 stowed length is about 8.7 m





30-m Reflector Mechanical and S/C Design

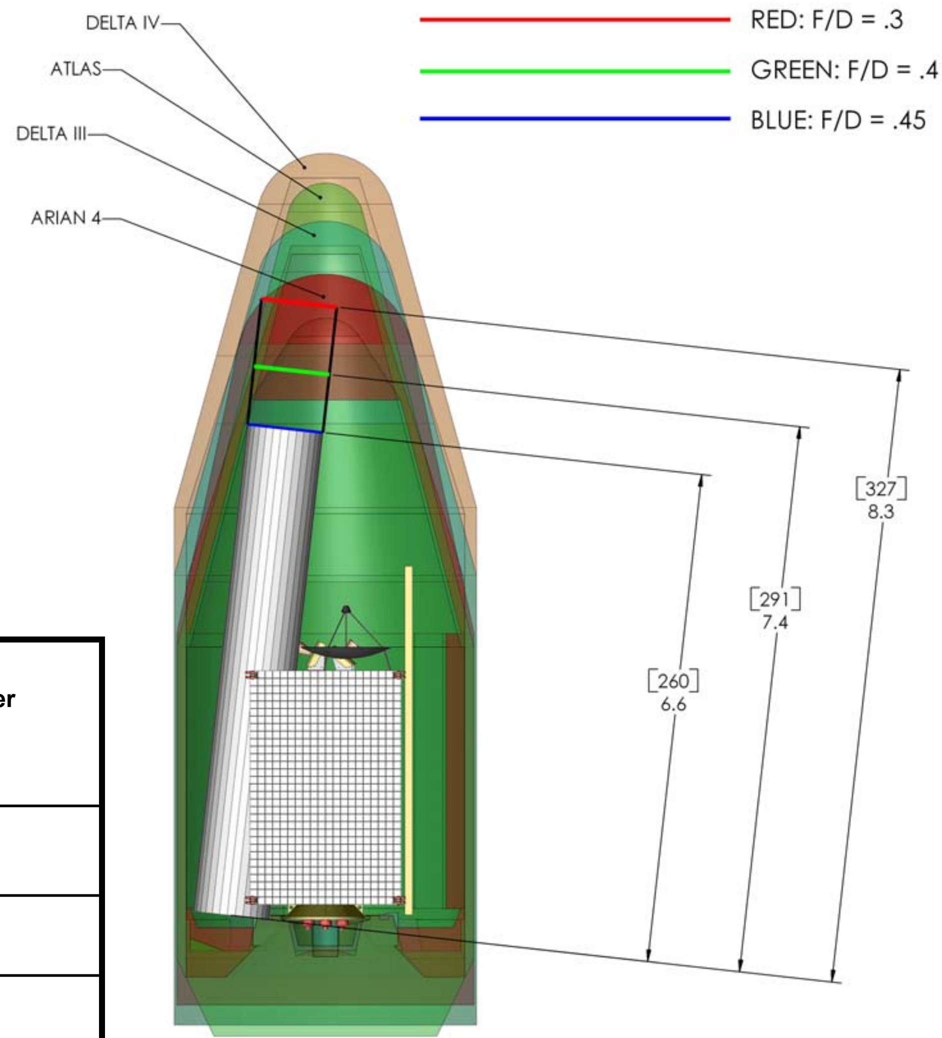
Stowed Configurations, Generic Spacecraft

F/D=.45
•Stowed Reflector fits all 4 example farings as tilted
•Booms expected to fit all envelopes but Arian

F/D=.4
•Stowed Reflector fits Delta III and IV
•May fit Atlas with additional tilt
•Booms expected to fit all envelopes but Arian

F/D=.33
•Stowed Reflector fits Delta IV
•May fit Delta III and Atlas with additional tilt
•Booms *may* only fit Delta IV

Focal to Diameter Ratio (F/D)	AM2 Reflector Stowed Length (meter)	AM2 Reflector Stowed Diameter (meter)
0.33	8.3	1.0 m
0.4	7.4	1.0 m
0.45	6.6	1.0 m



Hussein/Thompson

30-m Reflector Mechanical and S/C Design

Stowed Configuration, T310 Spacecraft

- Notional Concept to reflect relative sizes
- Complement of P/L hardware needs refinement (e.g. Comm hardware (X-band not shown), … etc

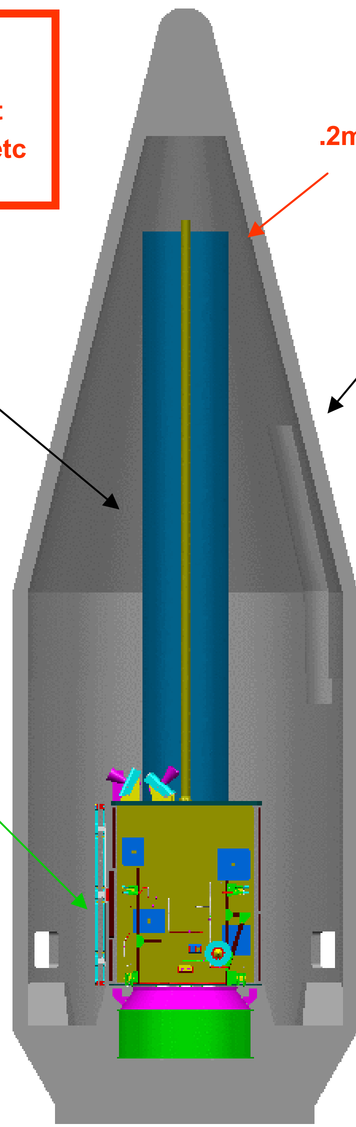
30m Circular AM2 Astro Mesh Reflector

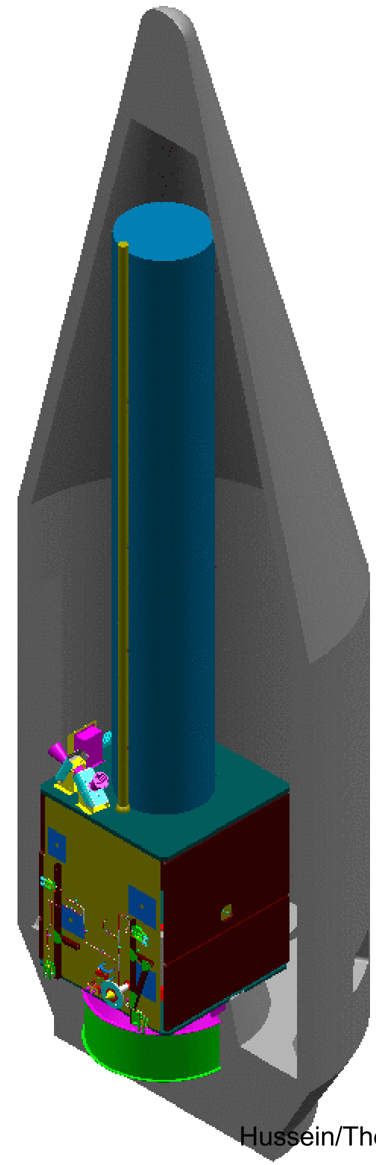
Stowed Batten: (1.0 dia x 6.6 length)m
Deployed: (30 dia x 6.4 length)m
F/d ratio: .45
Mass: 170 kg (reflector only)
159 kg (boom & tie-down)

Generic T310 S/C Bus
(5x Panel S/A Wing)
(1.7W x 1.7L x 2.1H)m

.2m Clearance

Atlas V4XX EPF
(EELV-M)

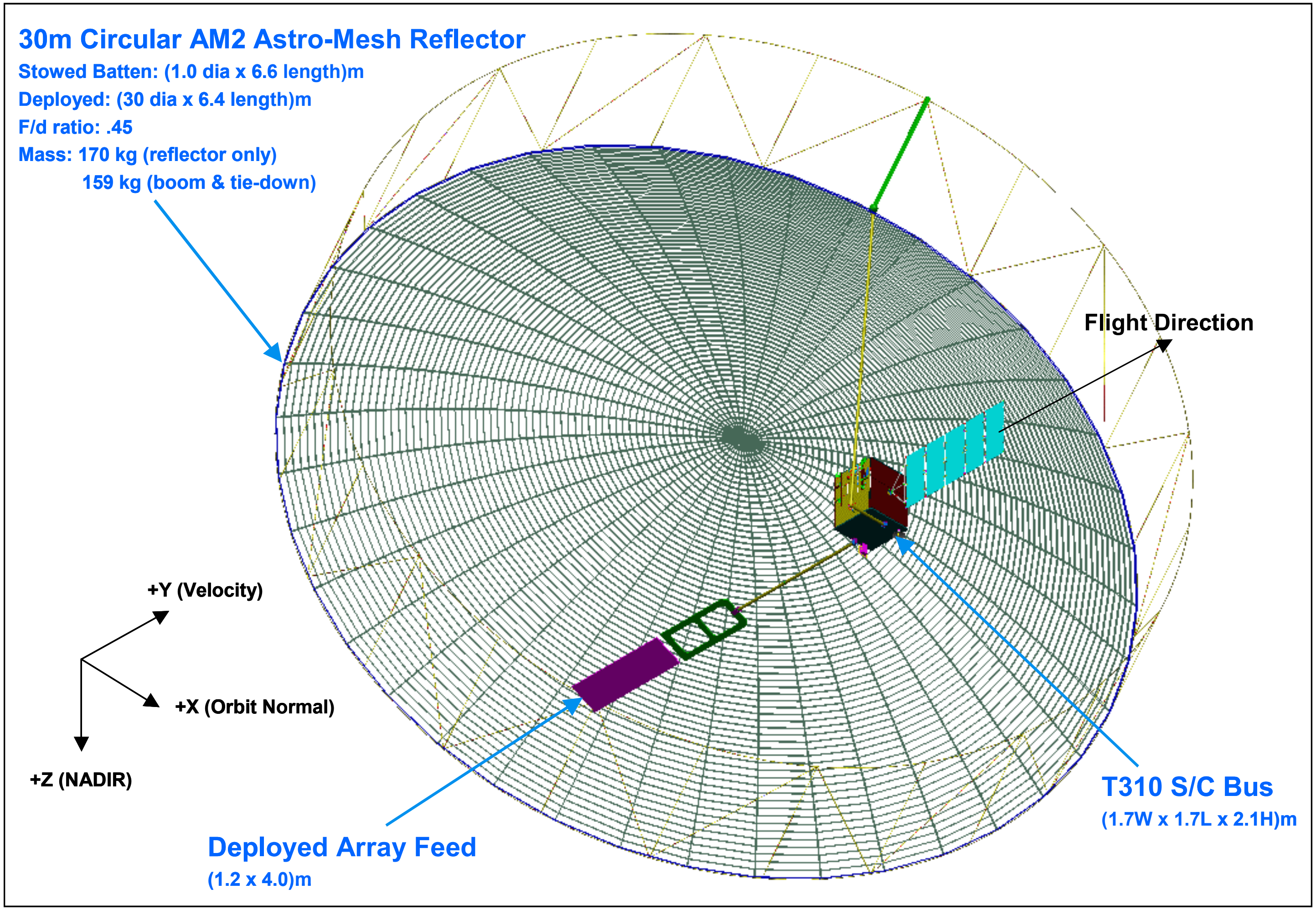




Hussein/Thompson/Parker

30-m Reflector Mechanical and S/C Design

Deployed Configuration



30-m Reflector Mechanical and S/C Design

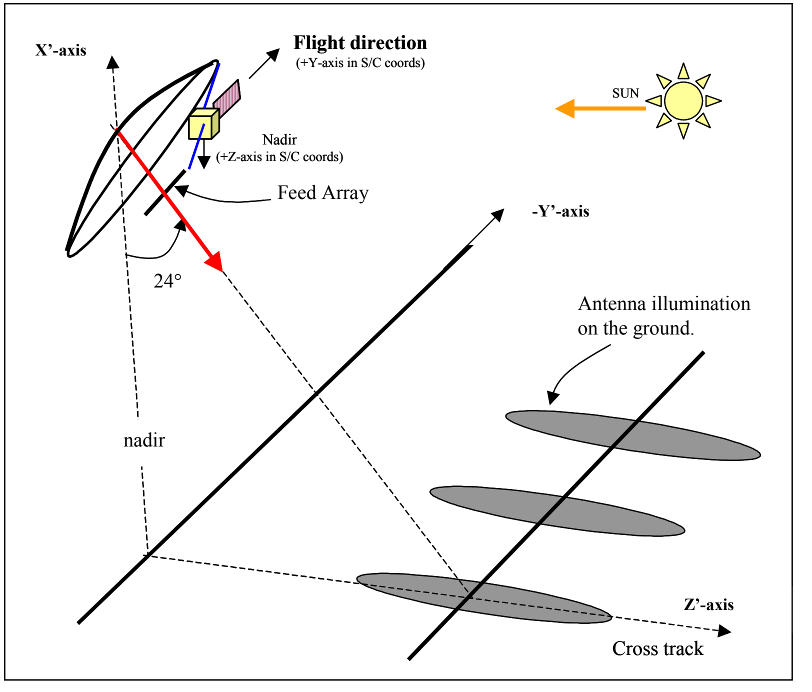
Why a circular aperture?

REFLECTOR TRADEOFF	Aperture Shape		
	Circular	**Elliptical**	**Rectangular**
Structure type	Heritage AstroMesh	Modified AstroMesh	Concept
Antenna mass	Minimum	~125% of heritage AstroMesh	High
Stowed volume	Minimum	Minimum	Large
Deployment	Relatively simple; synchronous	Relatively simple; synchronous	Complex; sequential
Mesh implementation	No discriminators	No discriminators	No discriminators
Low earth orbit	No discriminators	No discriminators	No discriminators
Heritage	Excellent	Moderate	Poor
Surface accuracy	High	Moderate to high	Sufficient
Cost	Relatively low	Higher	Highest
"Wasted" Aperture	High	Medium	None

30-m Reflector Mechanical and S/C Design

MOSS Mission Accommodation

- No stringent requirements on propulsion, electrical, and attitude control subsystems - can be accommodated with existing technology:
  - On-orbit delta-V requirements accommodated with a simplified version of a baseline dual-mode, pressure regulated, bi-prop propulsion subsystem
  - The 1313km 6am/6pm orbit has no eclipse, hence batteries are only needed during launch and prior to solar panel deployment.
  - The range of pointing requirements (1.0 deg required, 0.5 or 0.25 deg desired) can be supported by a simple earth-sensor and sun-sensor attitude reference system.
- The low data rate of the MOSS instrument allows a low demand on the solid state recorder and the downlink systems
- The mass of the reflector, boom, all mechanisms, and the dual-frequency feed is estimated to be about 450Kg.



Tower Radar

Objective

- Science Proof-of-Concept for future spaceborne system
- Prototype science data set to be constructed
  - VHF, UHF (P-band), and L-band (137, 435,1000 MHz) measurements at instrumented test sites
  - Test sites: Grassland, Forest Canopy, and Arid regions
  - Extensive "ground-truth" with *in-situ* probes
  - temporal correlation of in-situ and radar measurements with soil moisture
  - Will demonstrate wavelength-dependent radar penetration effectiveness for soil moisture observations
  - Absolute calibration requirement: **1.5 dB**
  - Measurement time period: **days to weeks**
  - Sampling interval: on order of **3-12 Hrs**

Tower Radar

Challenges

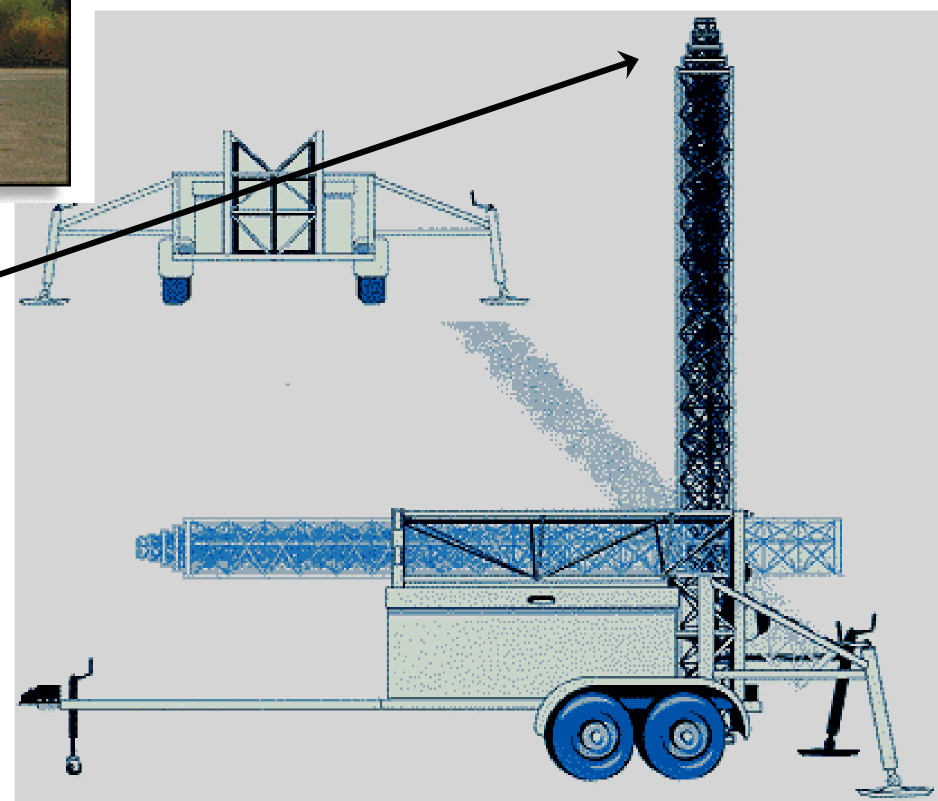
- Low frequency/Broadband
- Pulsed radar
- Limited height
- Tower mounted
  - Majority of vendors/components ham radio
  - High-speed low-frequency components scarce
  - High directivity antennas impractical
- Low frequency calibration a challenge

- Radar Mobility Requirements
  - Site to site, inter-site
  - Obtain Independent Samples
  - Constrain Incidence Angle Range
  - Capability to Perform onsite Calibration
    - Lake
    - Corner reflector
    - Signal generator

Tower Radar

Commercial Telescoping Tower

Tower was built by US Tower (Visalia, CA), and delivered to JPL in August 2002.



Log periodic Antenna mounts on top of telescoping tower, Max height 45m.

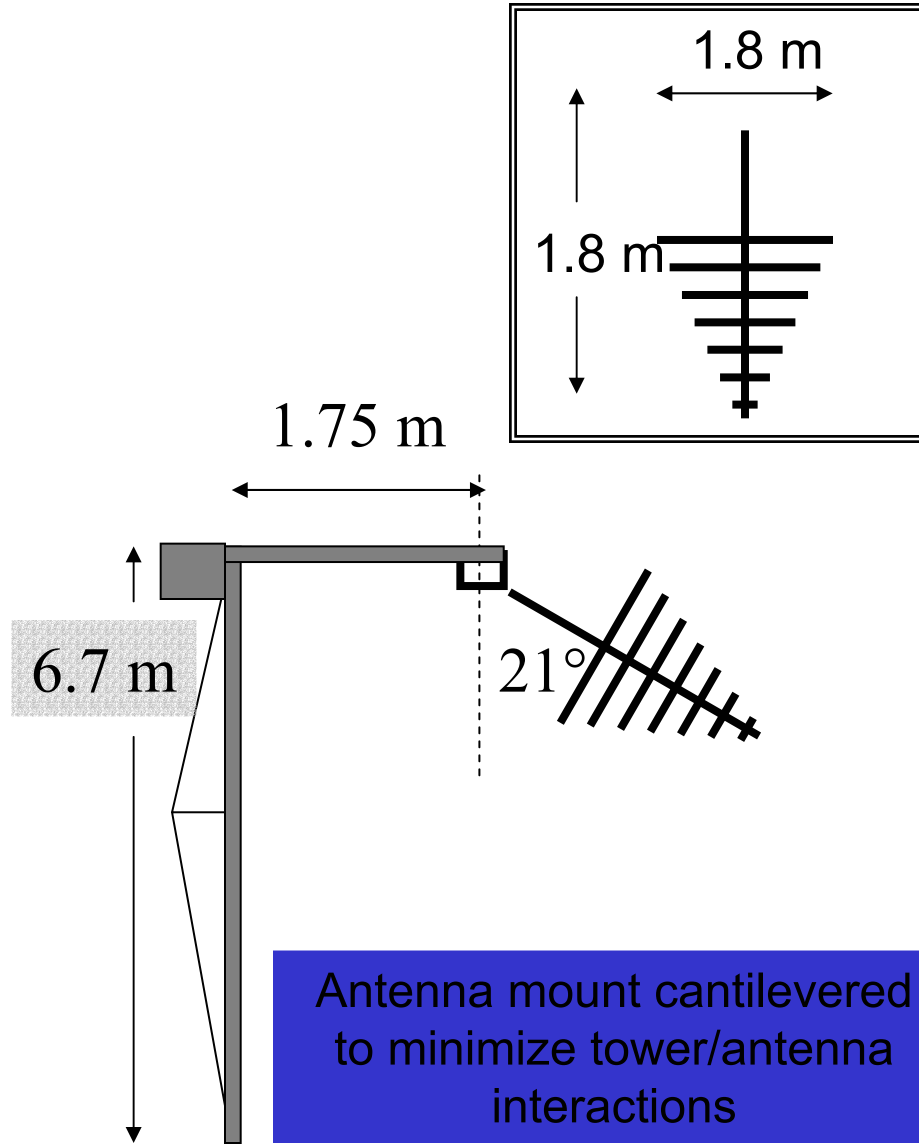
Height: 35m standard + 8m attachment

Hoffman

Status: Tower Radar

Dual-Pol Log Periodic Antenna (LPA) and Mount

Scientific Atlanta Antenna

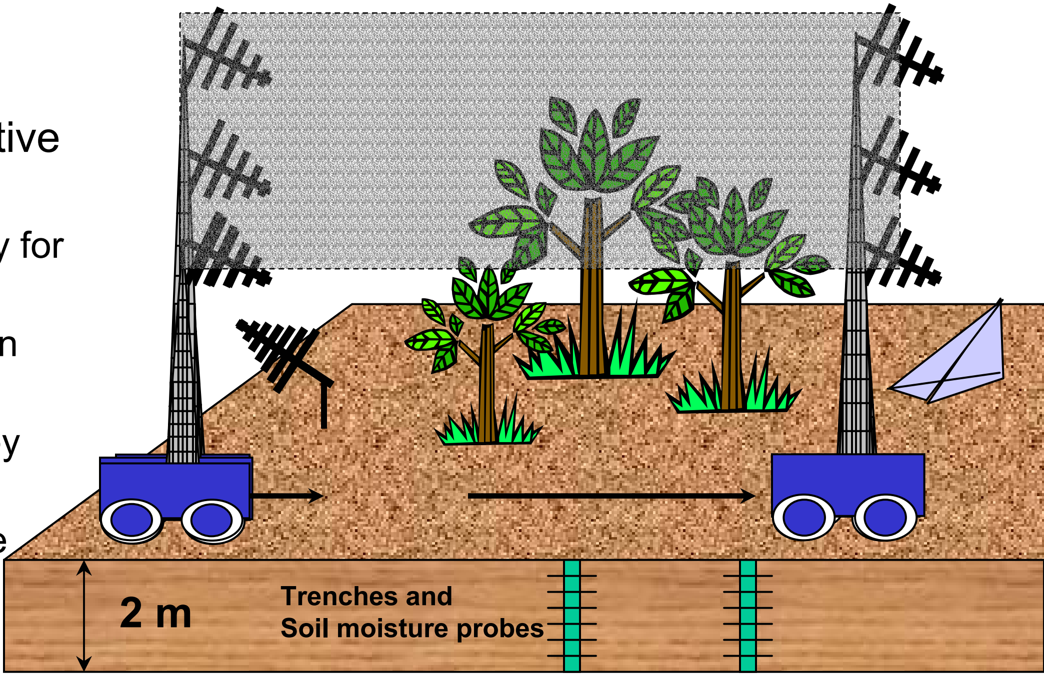


Antenna mount cantilevered to minimize tower/antenna interactions

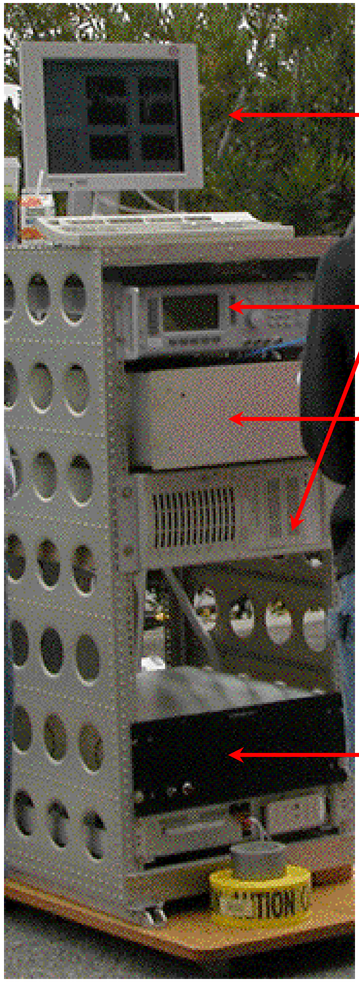
Tower Radar

Aperture Synthesis and Calibration

- To provide better beam focusing and collecting independent samples, a synthetic aperture is formed
- Tower will be moved up, down, and sideways to achieve a rectangular effective aperture
  - Nominal 10m vertical (but have capability for 20m)
  - Nominal 10m horizontal for each “pixel” in the azimuth (along-track) direction
  - Focused pixel size on the ground: 10m by 10m
  - Nominal look angle 25 degrees, but quite flexible due to wide antenna beamwidth
- Calibration will use external targets
  - Corner reflector (amplitude)
  - Signal generator (phase)



Integrated RF System and Tower



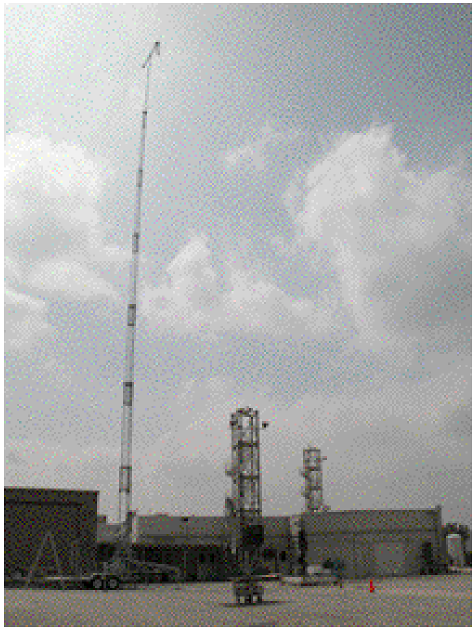
PC, control interface

synthesizer

RF electronics and digital system

Power supply

Tower deployment

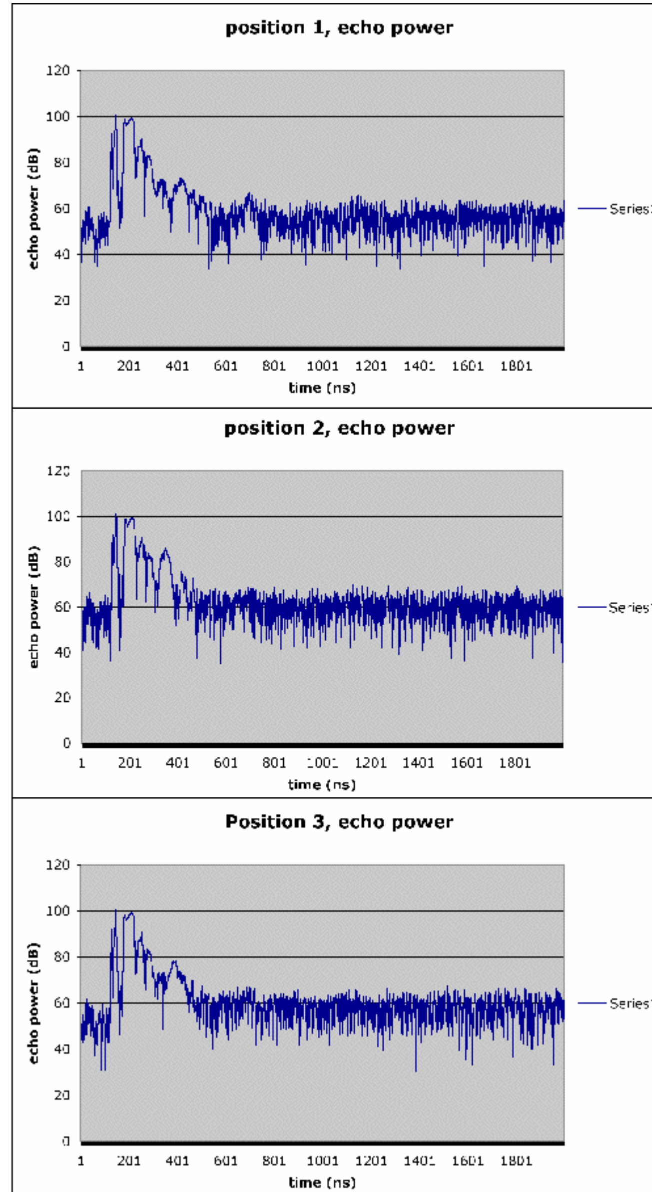


Tower at full extension
LPA mounted on top
Connected to RF system with 2m and 50m cables

Tower Radar

Sample Raw Data

- Figures show sample UHF echoes from different positions of antenna with respect to target, in this case a trihedral corner reflector. 100 pulses have been averaged.
- Custom processor has been developed for coherent aperture synthesis using raw data from each antenna/tower position
- Internal reflections were found to be too close in time to the target echoes, hence system underwent a redesign
- RFI is strong in urban environments, but expected to be lower at experiment sites



Tower Radar

Issues Encountered and Solved

- **Switches**
  - Short-pulse, fast-recovery, low-frequency switches are uncommon
  - Not designed for Tower Radar application
    - Could not achieve all specifications simultaneously with a single device
  - Used Multiple Switches in series to achieve desired specifications
- **Antenna**
  - Broadband antennas not designed for broadband pulsed radars
    - Custom designed antenna prohibitively expensive
    - Affordable off-the-shelf antennas not able to approach vendor specification or required specification across the frequency band from VHF to L-band
  - Refurbished an existing LPA, which meets specifications
- **Transmit internal reflections**
  - Field measurements indicated transmitter signal internal reflections were greater than were anticipated and significantly overwhelmed measurements of radar echos
  - Although such reflections are typical in RF systems, the problem in the present case was that due to large cable lengths, the reflections coincided with the target echoes
  - Problem has been mitigated by a redesign that places part of the RF electronics at top of the tower near the antenna to reduce time interval of internal bounce-backs. New design also increases SNR.

The MOSS Processor Challenges

- **The MossProc solution**: develop a new generation of radar processor for 3D radar measurements. The processor is similar to a microwave focusing microscope.
- **Processor features:**
  - Wide bandwidth focusing
  - Interference removal
  - 2-D and 3-D focusing (subsurface imaging?)
  - Calibration
  - Real time operation and debugging
- **MossProc combines imaging and parameter inversion**

Focusing Recipe

Focusing recipe: for each receiver position and each target location, make the phase correction

$$exp\left[2ik\left|\mathbf{r}_n - \mathbf{r}_T\right|\right]$$

$k = \frac{2\pi}{\lambda}$ $\mathbf{r}_n$ **Antenna n position** $\mathbf{r}_T$ **Target position**

Question: What is λ for a wide-band radar?

Most (narrow band) processors use the center frequency for the wavelength. This is not appropriate for MossProc.

Spectral Domain Return Signal

- Instead of focusing in the time domain, focus in the spectral domain!
- After down-conversion and Fourier transforming, the return signal from a point target at an antenna is given by

$$E(\omega)=\frac{G^2 \exp[-2i\omega r/c]W(\omega)H(\omega)\sigma(\omega)}{r^2}$$

G^2 2-way antenna gain (including phase)

$W(\omega)$ Transmit pulse spectrum

$H(\omega)$ System frequency response

$\sigma(\omega)$ Radar cross section (possibly frequency dependent)

Spectral Domain Focusing

- For a point target, the focused estimate of the cross section is given by

$$\sigma(\omega) = \frac{1}{N} \sum_{n=1}^{N} \underbrace{E_n(\omega) e^{i\Phi_n}}_{\text{Focusing}} \underbrace{M_n(\omega)}_{\text{Amplitude Compensation}}$$

Focusing

Amplitude Compensation

$$M_n(\omega) = \left[\frac{G_n^2(\omega) W(\omega) H(\omega)}{r_n^2} \right]^{-1}$$

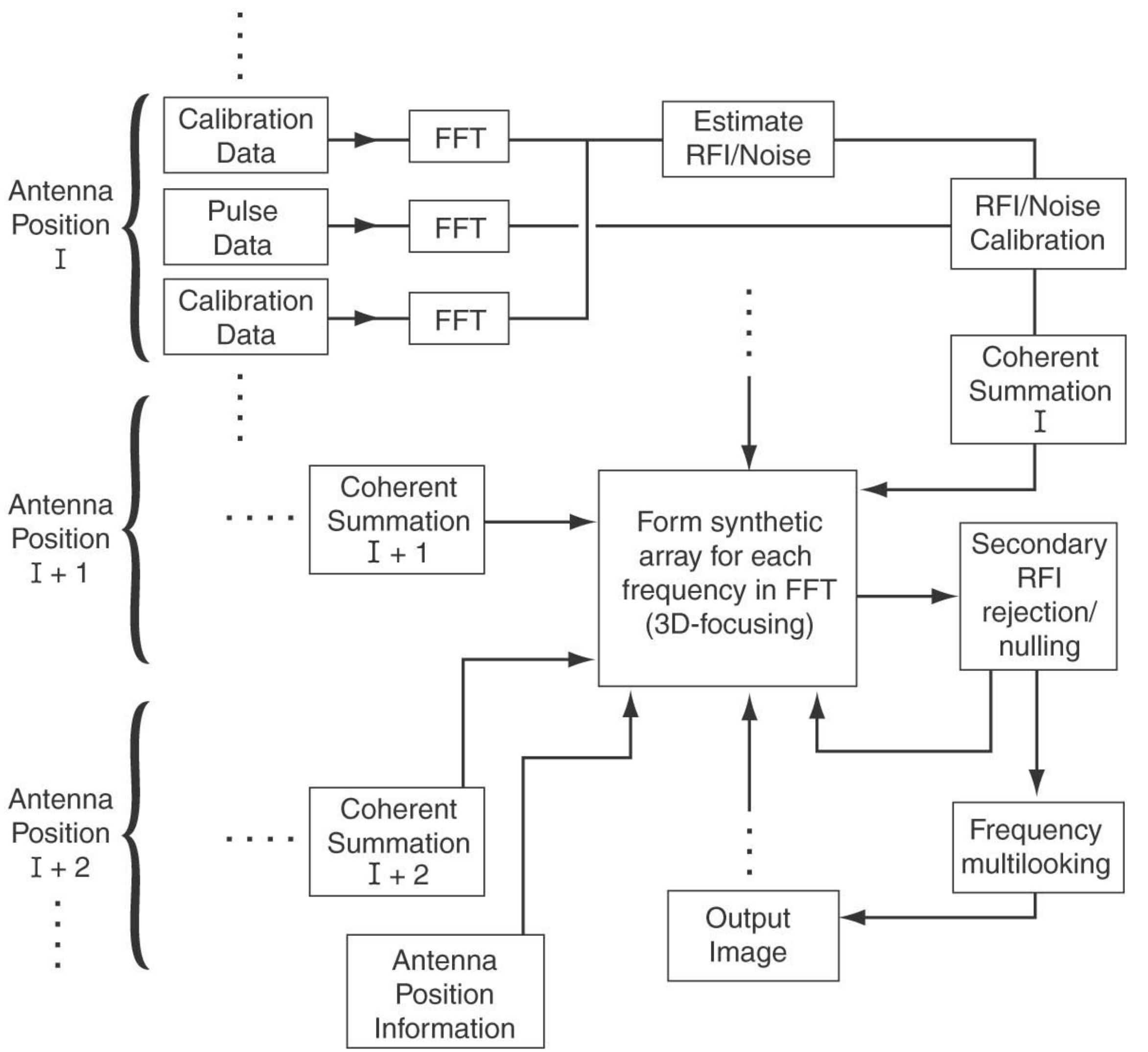
Inverse system frequency response

$$\Phi_n = 2\omega r_n / c$$

N: Total number of antenna positions

Tower Radar Processor

Processor Architecture

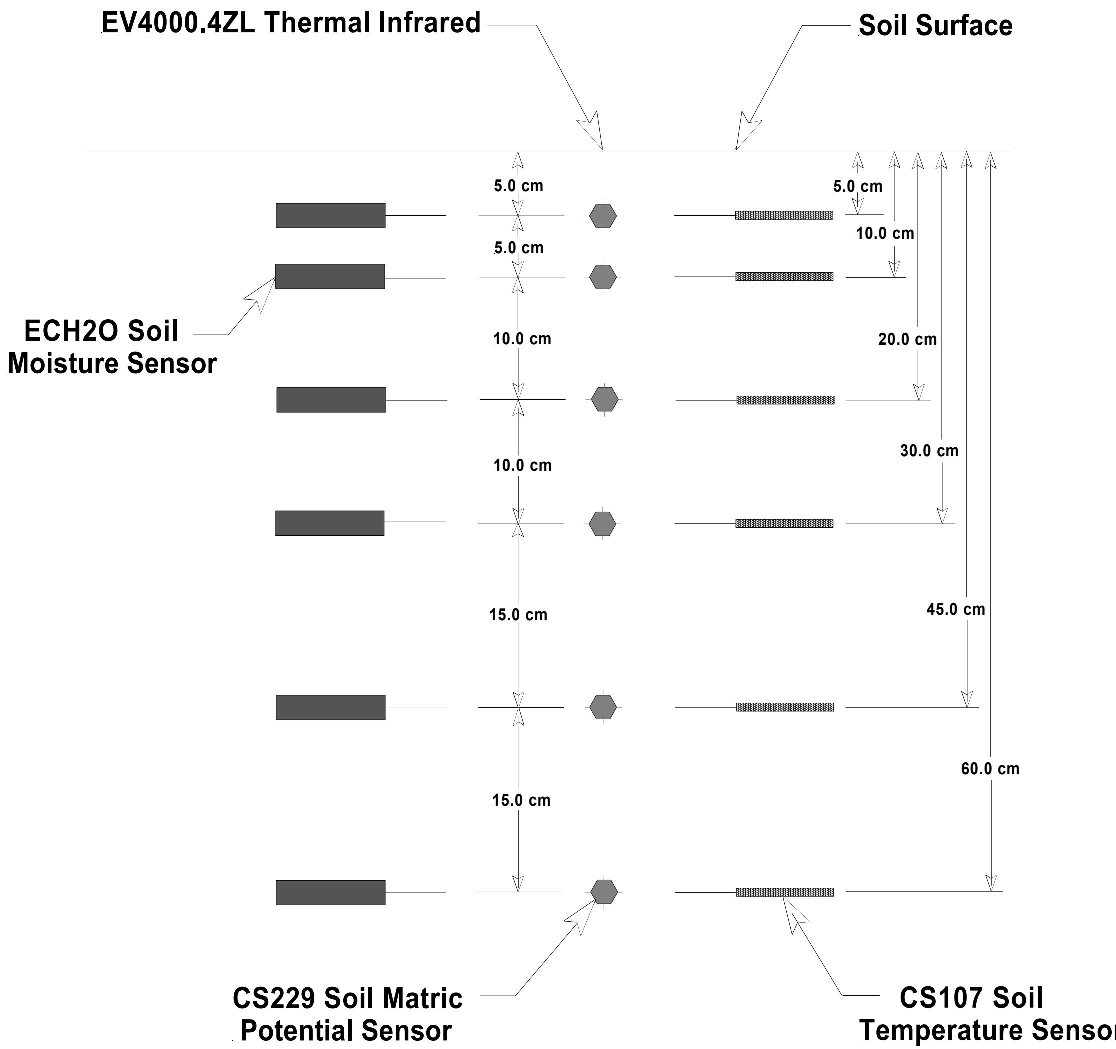


In-Situ Soil Moisture Measurements

Experiment Sites

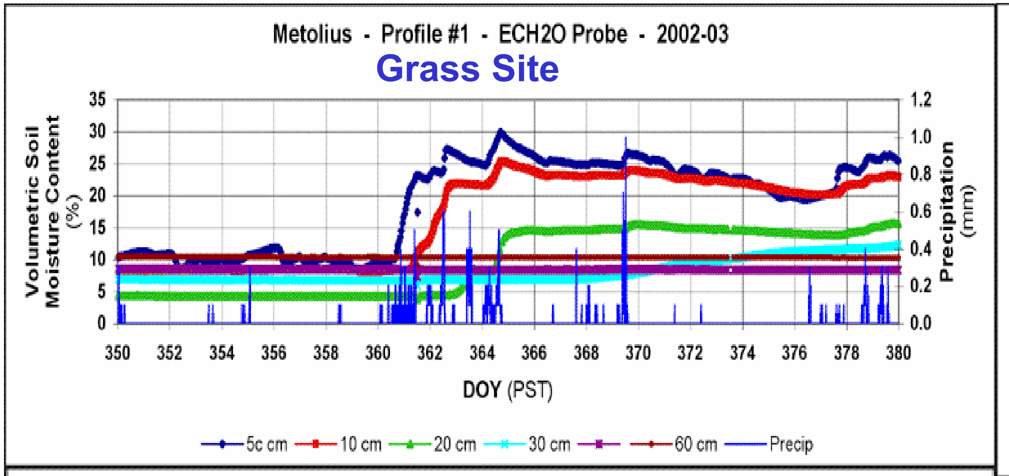
In-Situ Soil Moisture Measurements

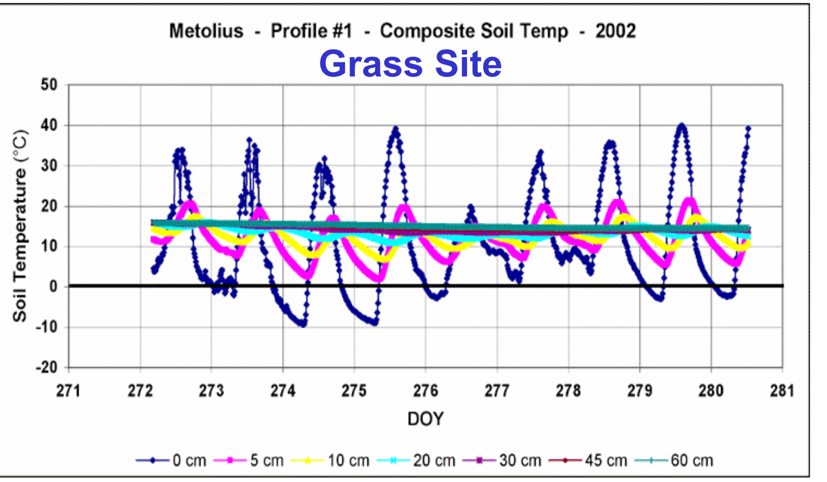
Probe setup in Oregon sites
Similar setup in Kansas and NOBS, but to 125 cm depth

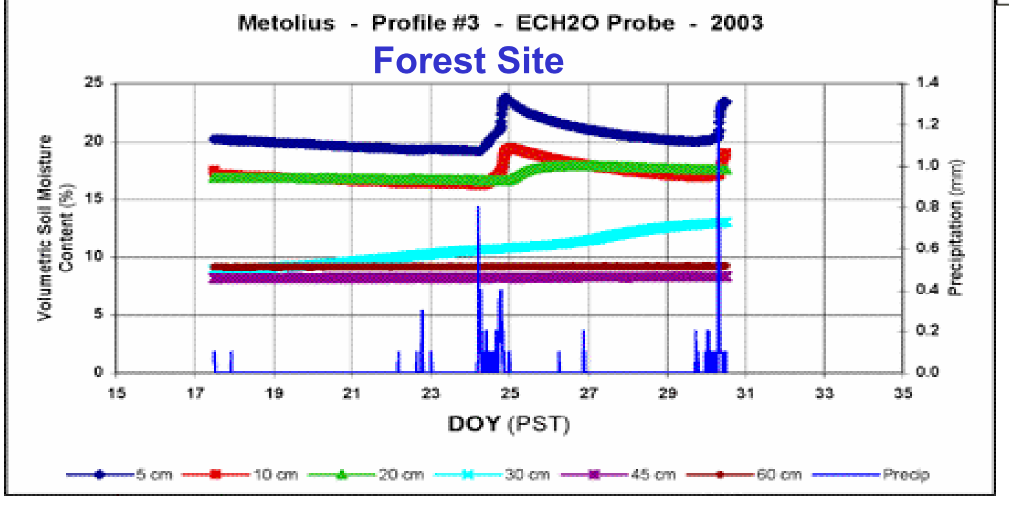


In-Situ Soil Moisture Measurements

Sample Data from Metolius, Oregon







Cuenca

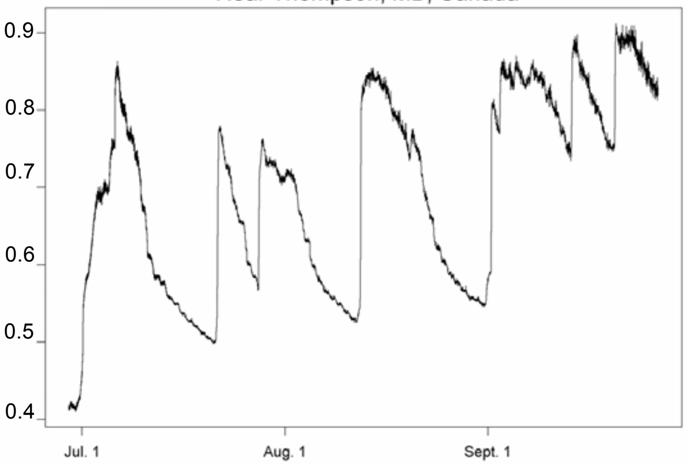
MOSS, ESTC 2003

In-Situ Soil Moisture Measurements

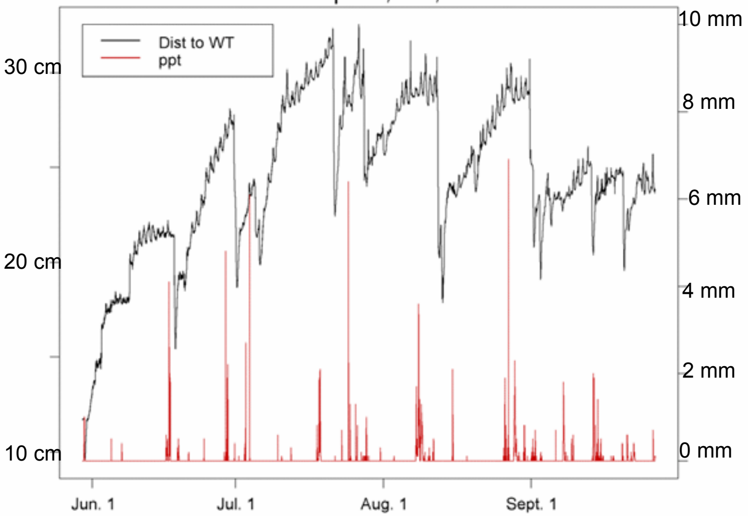
Sample Data from NOBS, Manitoba

- Study site contains a large store of soil organic carbon up to 8000 years in age
- Water table is generally fairly high, inhibiting decomposition of organic matter
- New research effort seeks to quantify the role of soil moisture and water table on the decomposition of these large organic carbon stores

Summer 2002 soil moisture at 25cm, Sphagnum bog
Near Thompson, MB, Canada



Summer 2002 distance to water table, Sphagnum bog
Near Thompson, MB, Canada



- Measurements made at this site include
  - water table depth
  - soil moisture profile
  - soil temperature
  - will include low-stature CO_2 fluxes

Dunn/Wofsy

Science Algorithms and Analyses

Ongoing Activities

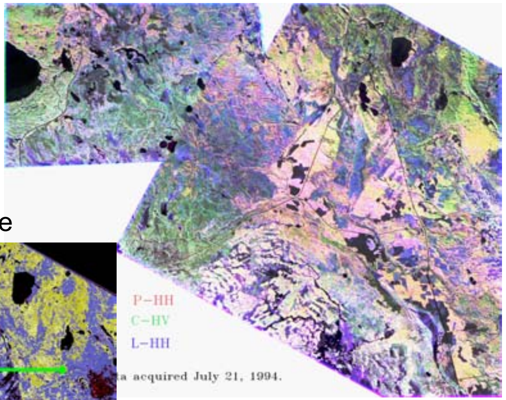
- Soil moisture estimation algorithms (JPL)
- Ionospheric Effects and calibration (JPL)
- Assimilation studies (MIT)
- Effects of deep soil moisture information on improving estimates of partitioning of global water into various components, especially evapotranspiration and drainage (Boston University)
- Study of the interplay of soil hydrologic state and boreal carbon decomposition (Harvard University)

Science Algorithms and Analyses

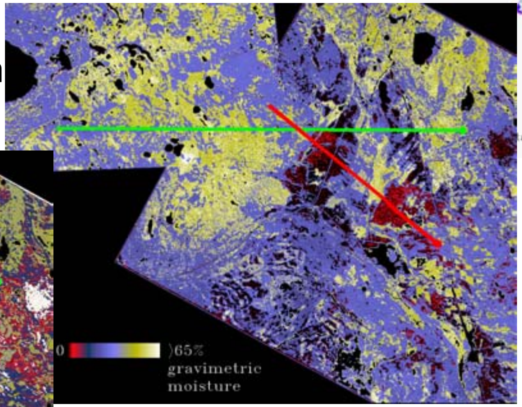
Soil moisture estimation algorithms

- Our existing algorithms are being adapted to MOSS study sites by integrating multiple vegetation and soil types
- Sensitivity analyses are being performed by simulating a large space of possible vegetation and soil conditions
- Numerical model for complex layered soil model is being developed to incorporate into existing vegetation scattering model

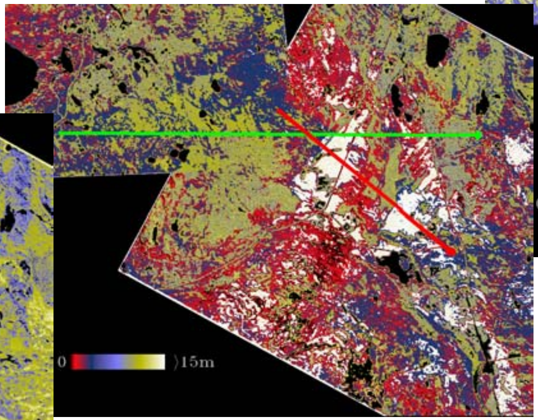
AIRSAR data from BOREAS



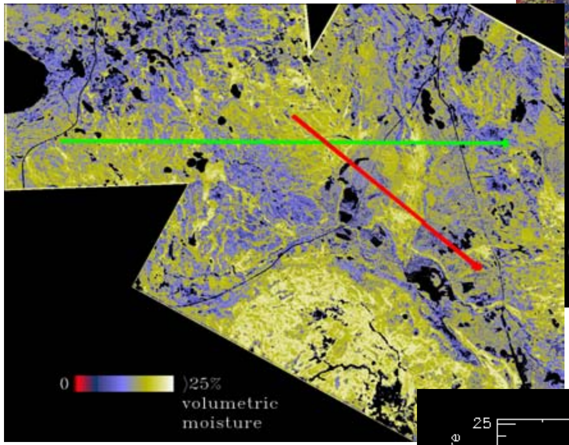
Estimated crown moisture

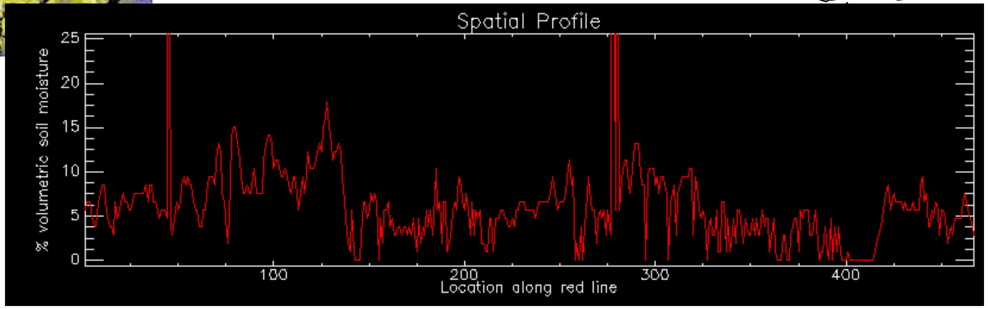


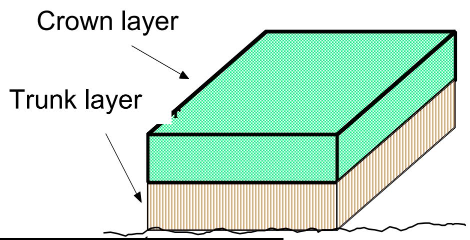
Estimated canopy height

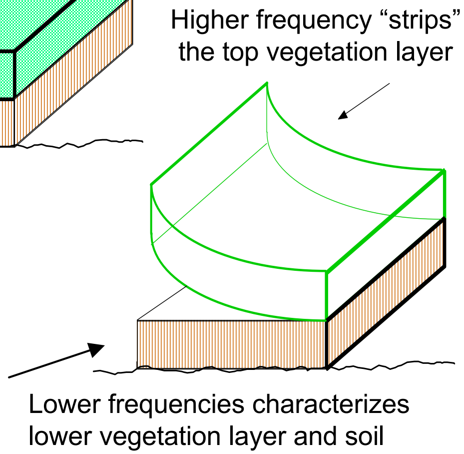


Estimated soil moisture





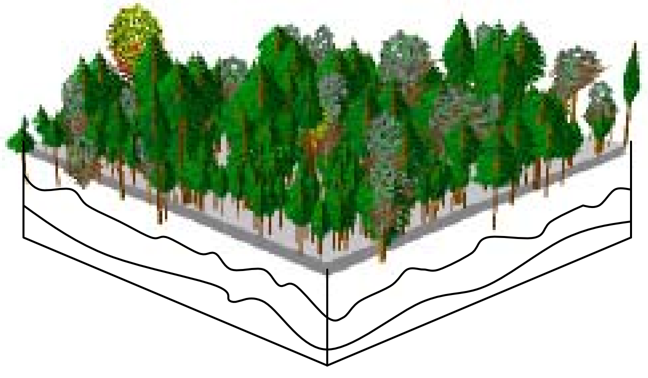


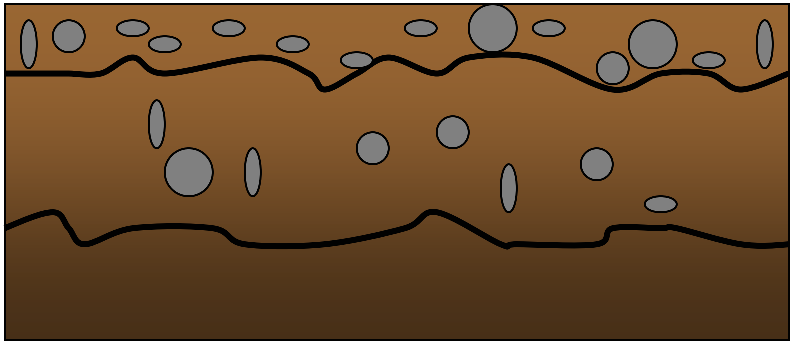


Science Algorithms and Analyses

Soil moisture estimation algorithms

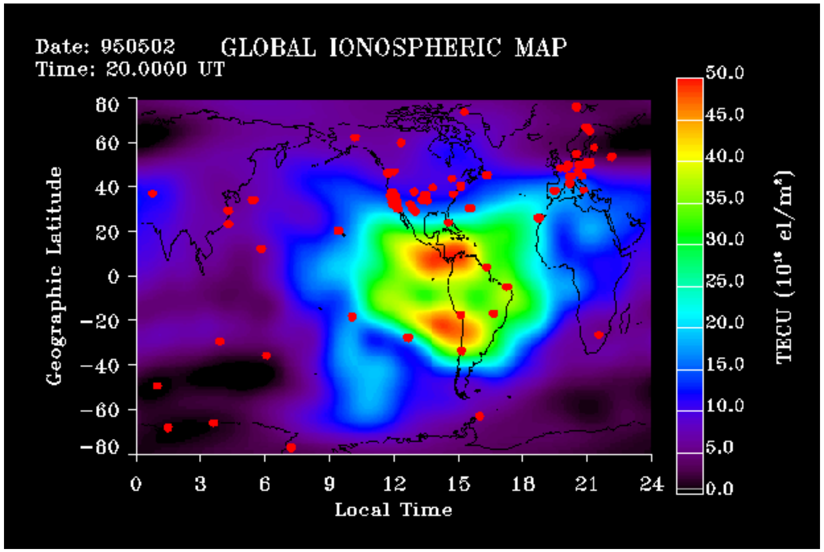
- Previous algorithms have used a single soil layer with a rough air-soil interface. No inhomogeneities in soil have been included.
- Numerical model for complex layered soil model is being developed that includes
  - Multiple rough interfaces to model soil layers (including bedrock and permafrost)
  - Rocks and other inclusions
- This is a complex problem and needs a numerical solution
- The solution is being implemented using the finite-difference time-domain (FDTD) method
- Will be integrated with existing forest scattering model
- Will investigate how to incorporate the soil/vegetation model with the 3D tower radar processor

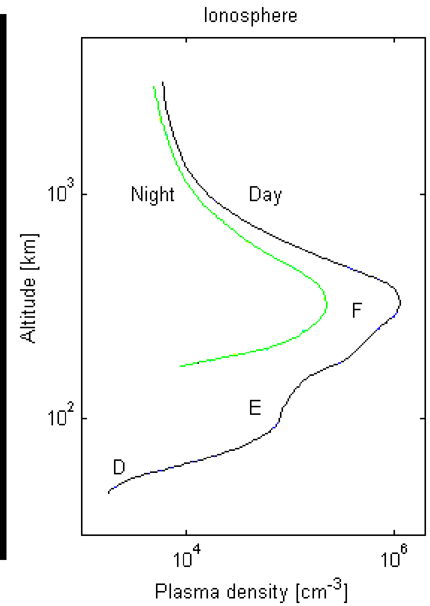




Modeled Subsurface Cross Section

Ionospheric effects and calibration





Ionosphere Parameters:

1. Ionospheric disturbances have a vertical scale from m to 400 km.
2. Disturbances can travel with a speed of 100m/s horizontally.
3. Existing measurements of TEC are performed at >100 spatial scale at <10% accuracy.
4. In low solar activity TEC varies from 4-8 TECU to 10-30 TECU
5. In medium to high solar activity TEC varies 8-12 TECU at night to 30-50 TECU at midday.

Possible effects of the ionosphere on SAR systems:

- **Azimuth Resolution**: Ionospheric turbulence reduces coherent length when it becomes smaller than the equivalent aperture size, the azimuth resolution is no longer D/2 (D is antenna diameter).
- **Range Resolution**: Image shift is significant because of ionospheric effect on group delay, pulse broadening and multiple scattering to range resolution are negligible.
- **Faraday Rotation**: Rotation of the plane of polarization is significant and inversely proportional to square of frequency.

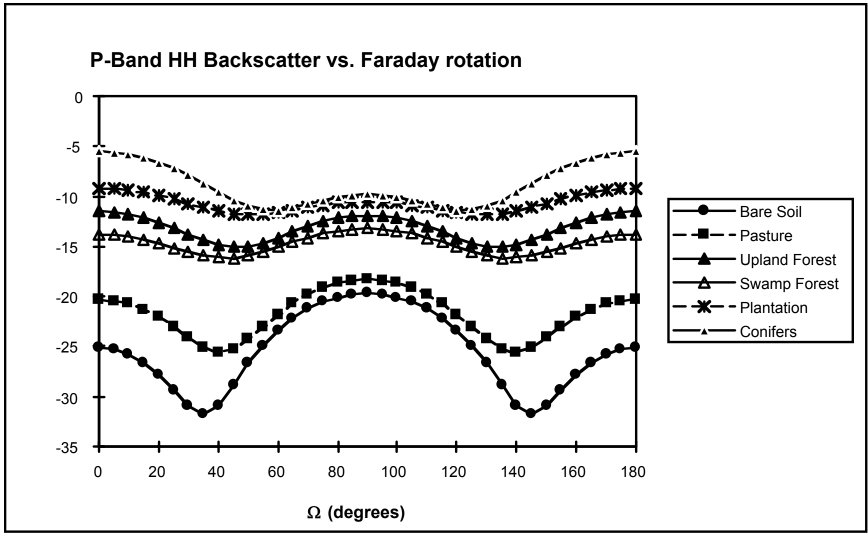
Ionospheric effects and calibration

Calibration of SAR Data for Faraday Rotation in Polarimetric Mode:

$$\begin{bmatrix} M_{hh} & M_{vh} \\ M_{hv} & M_{vv} \end{bmatrix} = \begin{bmatrix} \cos\Omega & \sin\Omega \\ -\sin\Omega & \cos\Omega \end{bmatrix} \begin{bmatrix} S_{hh} & S_{vh} \\ S_{hv} & S_{vv} \end{bmatrix} \begin{bmatrix} \cos\Omega & \sin\Omega \\ -\sin\Omega & \cos\Omega \end{bmatrix}$$

$$\Omega = \frac{1}{2}\tan^{-1}\left[\frac{(M_{vh} - M_{hv})}{(M_{hh} + M_{vv})}\right]$$

Calibration is only possible with polarimetric data



	Midnight		Midday	
	Minimum	Maximum	Minimum	Maximum
$f_c(MC/S)$				
N (electrons/m^3)	0.31×10^{12}	1.004×10^{12}	1.5×10^{12}	2.79×10^{12}
I_s (electrons/m^2)	0.93 x 10^{17}	3.1 x 10^{17}	4.5x 10^{17}	8.37 x 10^{17}
Ω_C (degrees)	0.15°	0.52°	0.76°	1.4°
Ω_L (degrees)	2.8°	9.48°	13.76°	25.6°
Ω_P (degrees)	22.9°	76.6°	111.2°	206.5°
Ω_{VHF} (degrees)	263.1°	876.8°	1272.8°	2367.4°

Saatchi

Assimilation studies (MIT)

Measurement Requirement Definitions and Development of Data Assimilation System for Geophysical Retrievals

Statement of Objective:

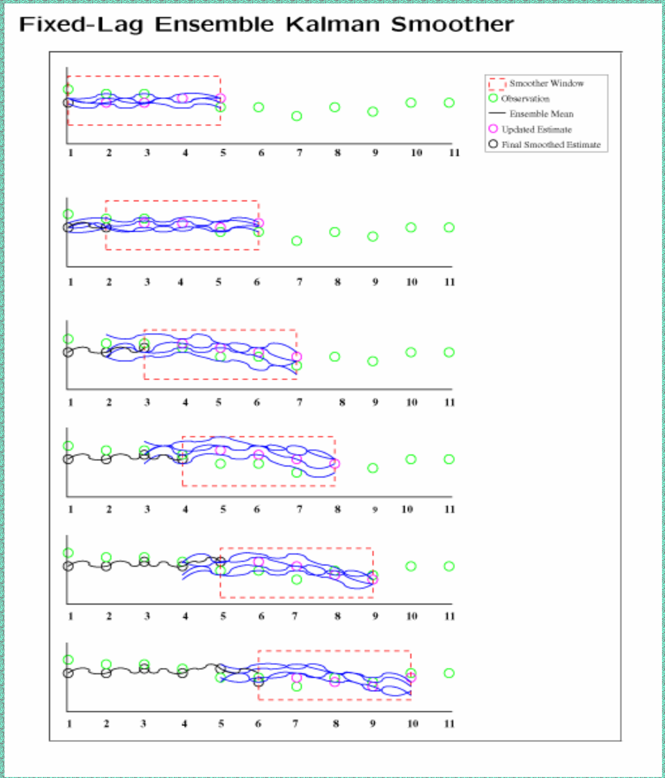
Quantify the measurement requirements using an **Observing System Simulation Experiment (OSSE)**

Demands on the OSSE:

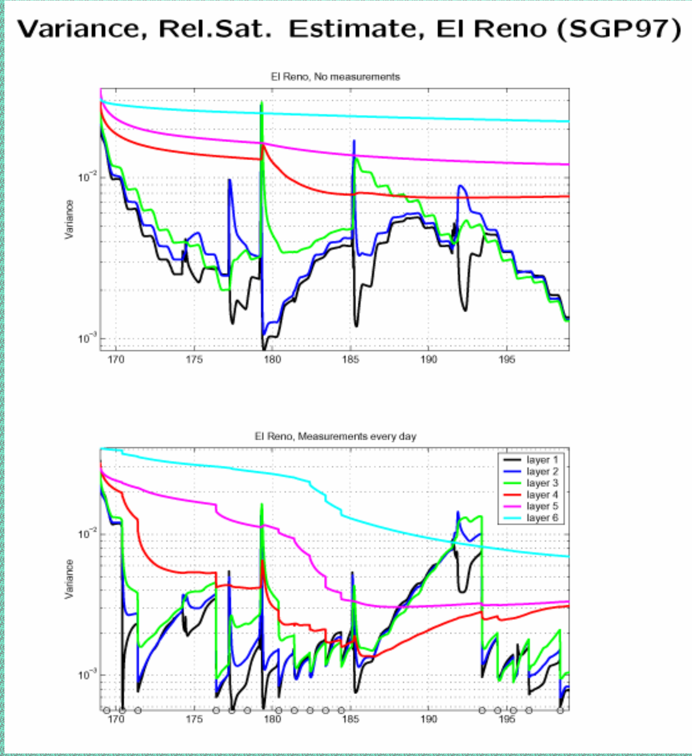
1. Simulate fields and profiles of soil moisture whose dynamic in time and space are in response to micrometeorological forcing and given soil and vegetation characteristics
2. Implement using data from intensive hydrologic field experiment (SGP97, SGP99, and SMEX02) observations and from project field campaigns
3. Produce forward model data on simulated instrument measurements
4. Implement and test inverse model retrieval of soil moisture profiles under vegetation canopy

Assimilation studies (MIT)

Implemented and tested data assimilation system capable of repeated pass over and inversion of measurements that are particularly required to update estimates of non-uniform soil moisture profiles



Estimate the inherent soil moisture variability at different depths in order to define measurement requirements; Assess the magnitudes of retrieval error given different sensor and system characteristics in trade-off studies



Entekhabi/Dunne

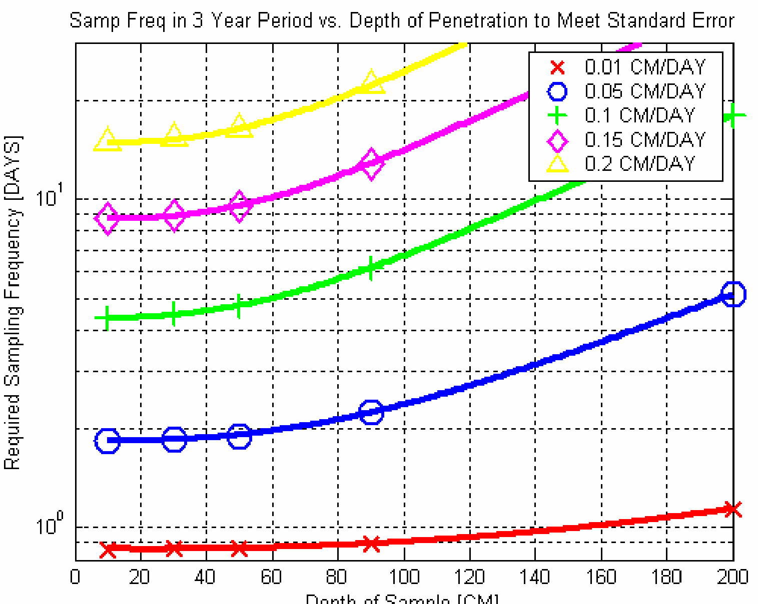
Temporal sampling requirements (Boston University)

Developed analytical model for estimating tradeoff between Depth of Moisture Measured and Frequency of Sampling

- Under Markovian assumption for soil moisture dynamics at daily time scale, estimated the variance of sample-mean water balance closure (e.g. cm/day of error) for models using sparsely sampled atmospheric forcing and soil moisture.
- Variance depends on persistence of moisture (represented by exponential decay parameter,f), variance of component of measured soil moisture (V) correlated with with flux of moisture, total time of experiment (T), and number of samples in that time (N).

Application Using Sparsely Sampled Moisture in IL Integrated from 10cm to 200cm depth

Note, for example following the blue lines with circles, that 200 cm moisture sampled every 5 days has the same impact on water balance estimation as 10cm soil moisture sampled every 2 days.



Salvucci

Summary

- Spaceborne SAR system parameters have been designed.
- Reflector and feed configuration has been designed at UHF/VHF and a scaled frequency set (S/L band).
- Dual stacked patch feed array has been designed. The scaled frequency array element has been built and tested, array is being currently built. The actual frequency element pre-prototype is being built using inexpensive foam substrate. Low-frequency prototype array will be built next year.
- 30-m mesh reflector mechanical design including all deployment mechanisms has completed first phase. Mass estimate for complete reflector+feed system is less than 400 Kg. Spacecraft options have been considered. Analysis will be refined next year.
- Tower radar was built. Field tests indicated internal reflection problems. A minor redesign has just completed. Initial test results indicate problem has been solved.
- Tower radar processor was designed and built, being refined to accommodate radar redesign.
- Next generation deep soil moisture estimation algorithms are being developed, to be tested with tower radar data.
- Assimilation studies that incorporate deep soil moisture data are under way.
- Science requirements on depth and repeat observation period are being refined based on results of evapotranspiration dynamics.
- Impact of data products on global climate change studies is being studied.